Signals and degeneracies of the primordial power spectrum: Neutrinos & Inflation

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Cosmology with the CMB and its Polarization

Fine Theoretical Physics Institute
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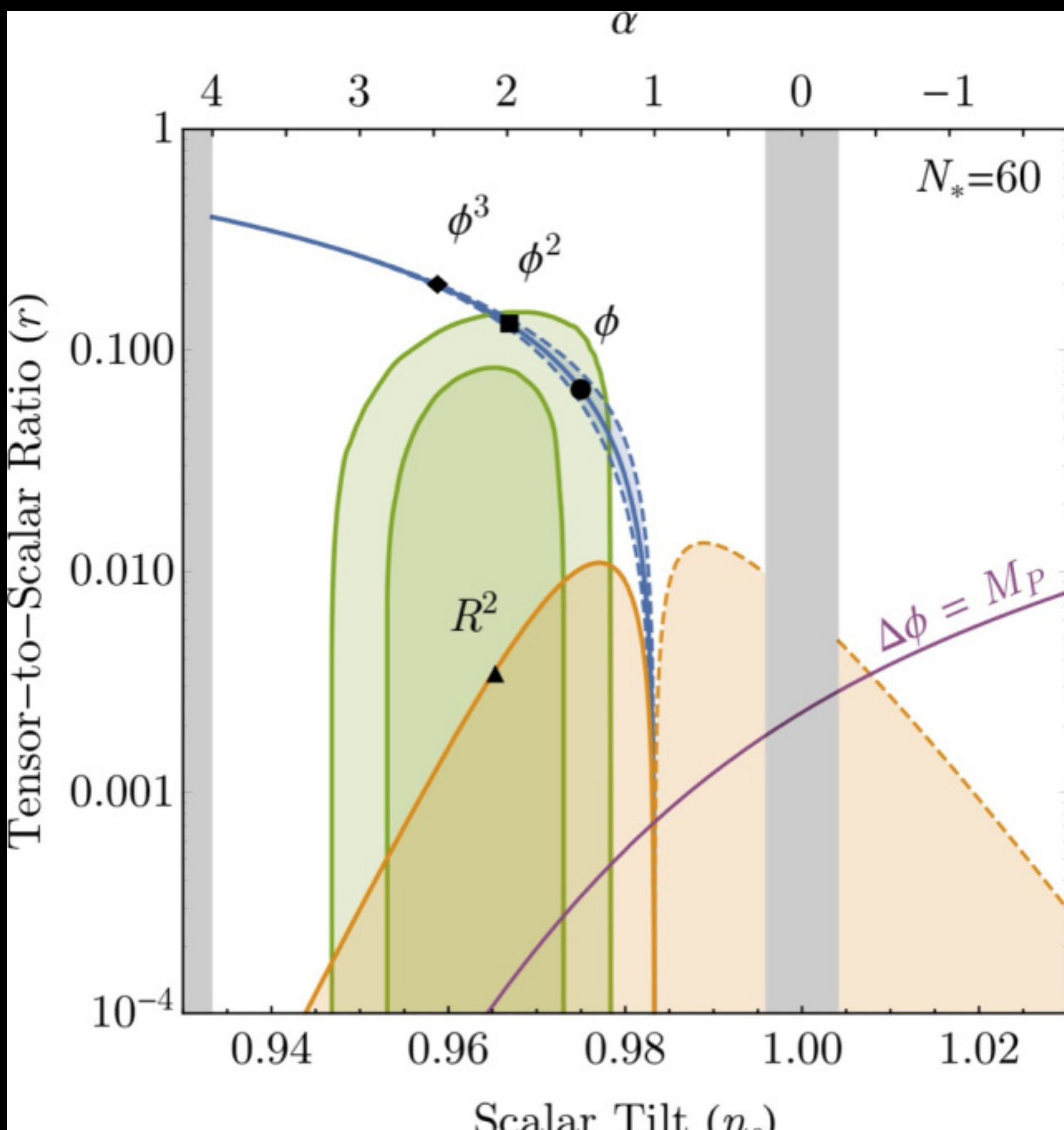
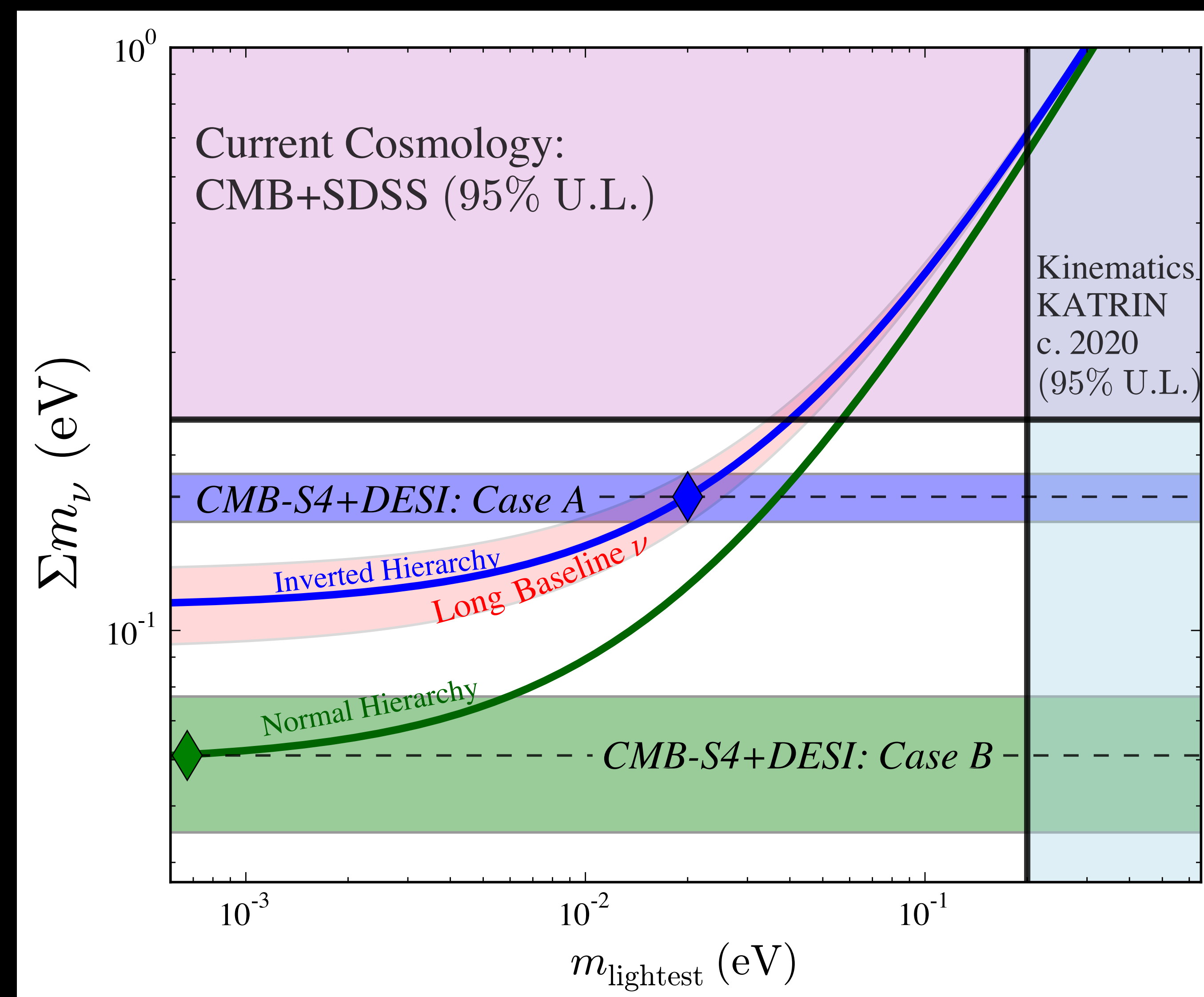
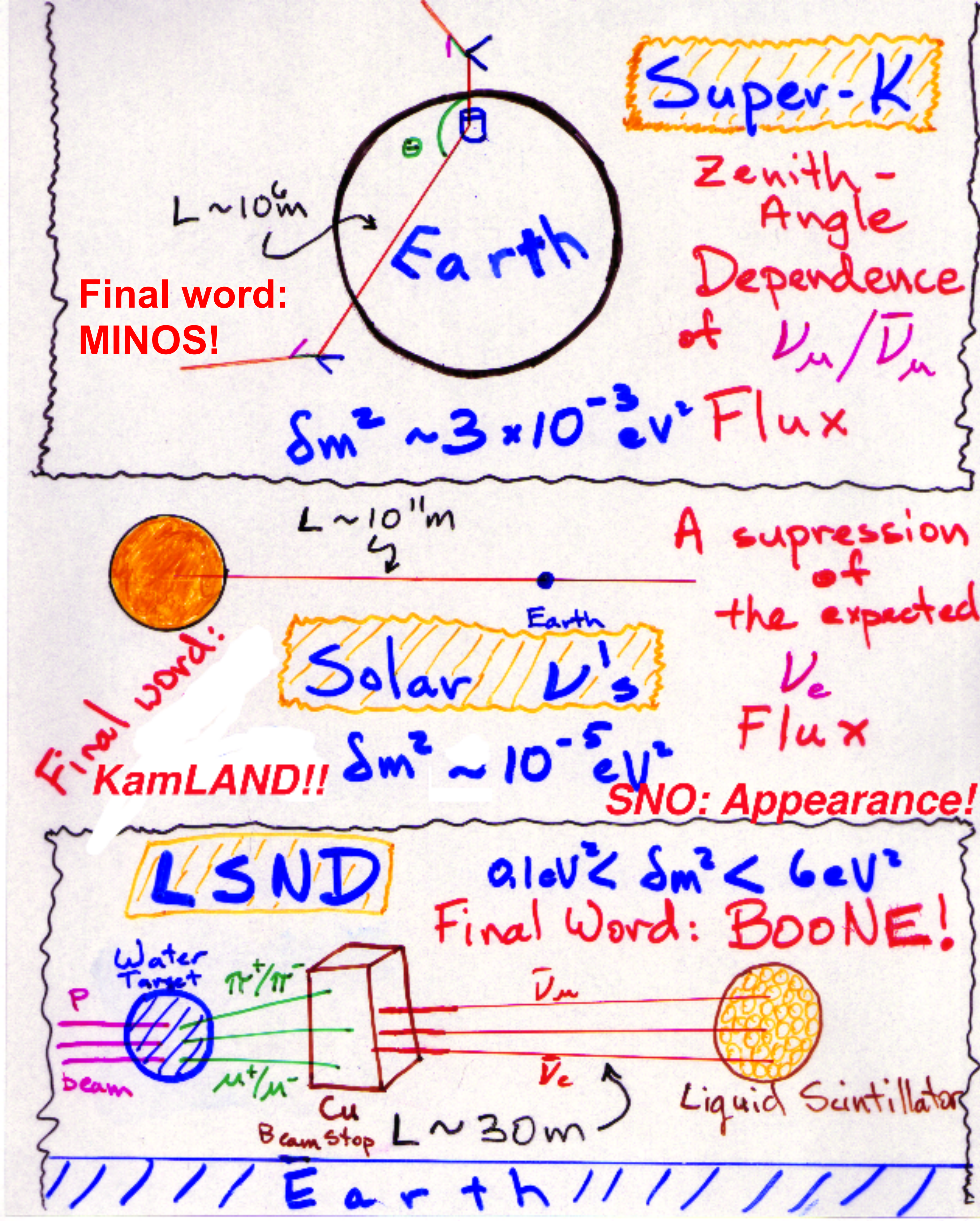
Two Fundamental Physics Goals of Cosmology

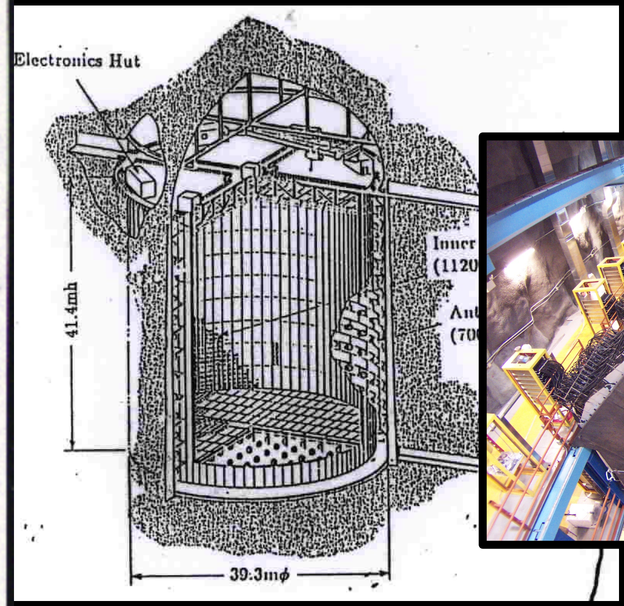
inflationary tilt & scalar-to-tensor ratio

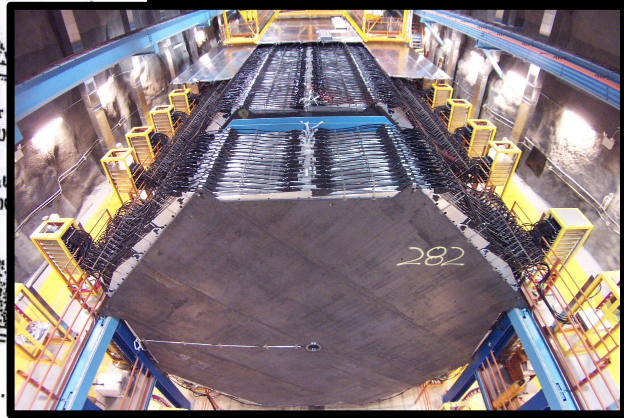
the absolute neutrino mass scale






Super-K
Zenith-Angle Dependence of $\nu_\mu/\bar{\nu}_\mu$ Flux
$L \sim 10^6$m
Earth
θ
Final word:
MINOS!
$\delta m^2 \sim 3\times10^{-3}$ eV^2
$L \sim 10^{11}$m
Earth
Solar ν's
A supression of the expected ν_e Flux
$\delta m^2 \sim 10^{-5}$ eV^2
Final word:
KamLAND!!
SNO: Appearance!
LSND
0.1 eV^2 < δm^2 < 6 eV^2
Final Word: BooNE!
Water Target
p
beam
π^+/π^-
μ^+/μ^-
Cu
Beam Stop
$\bar{\nu}_\mu$
ν_e
$L \sim 30$m
Liquid Scintillator
Earth


Electronics Hut
41.4mh
39.3mϕ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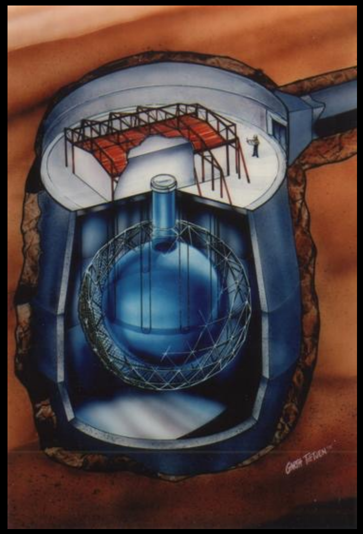
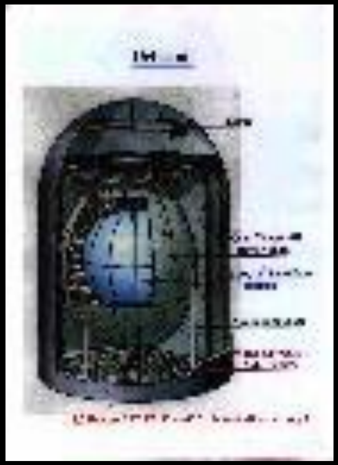
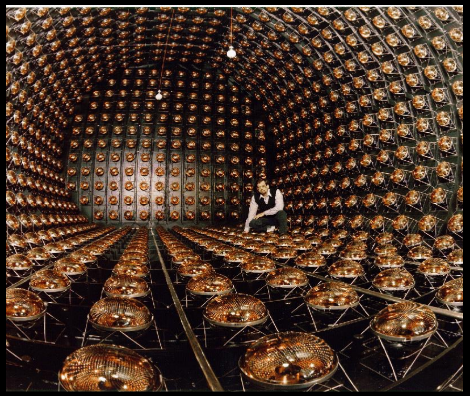
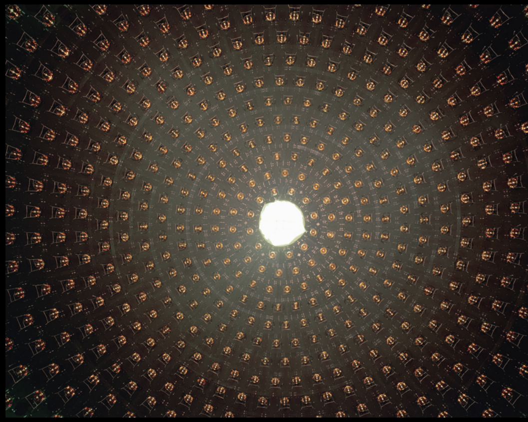
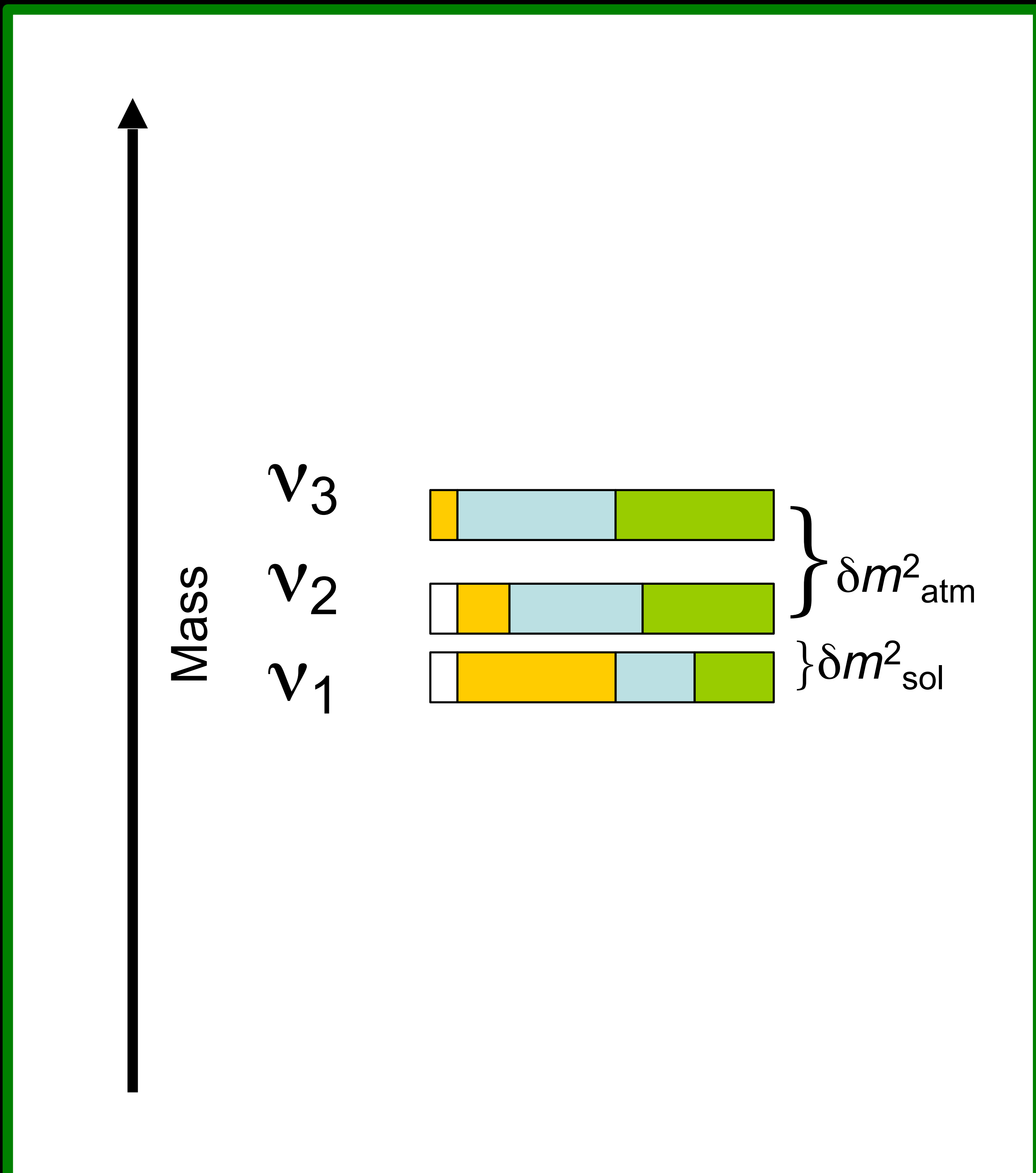


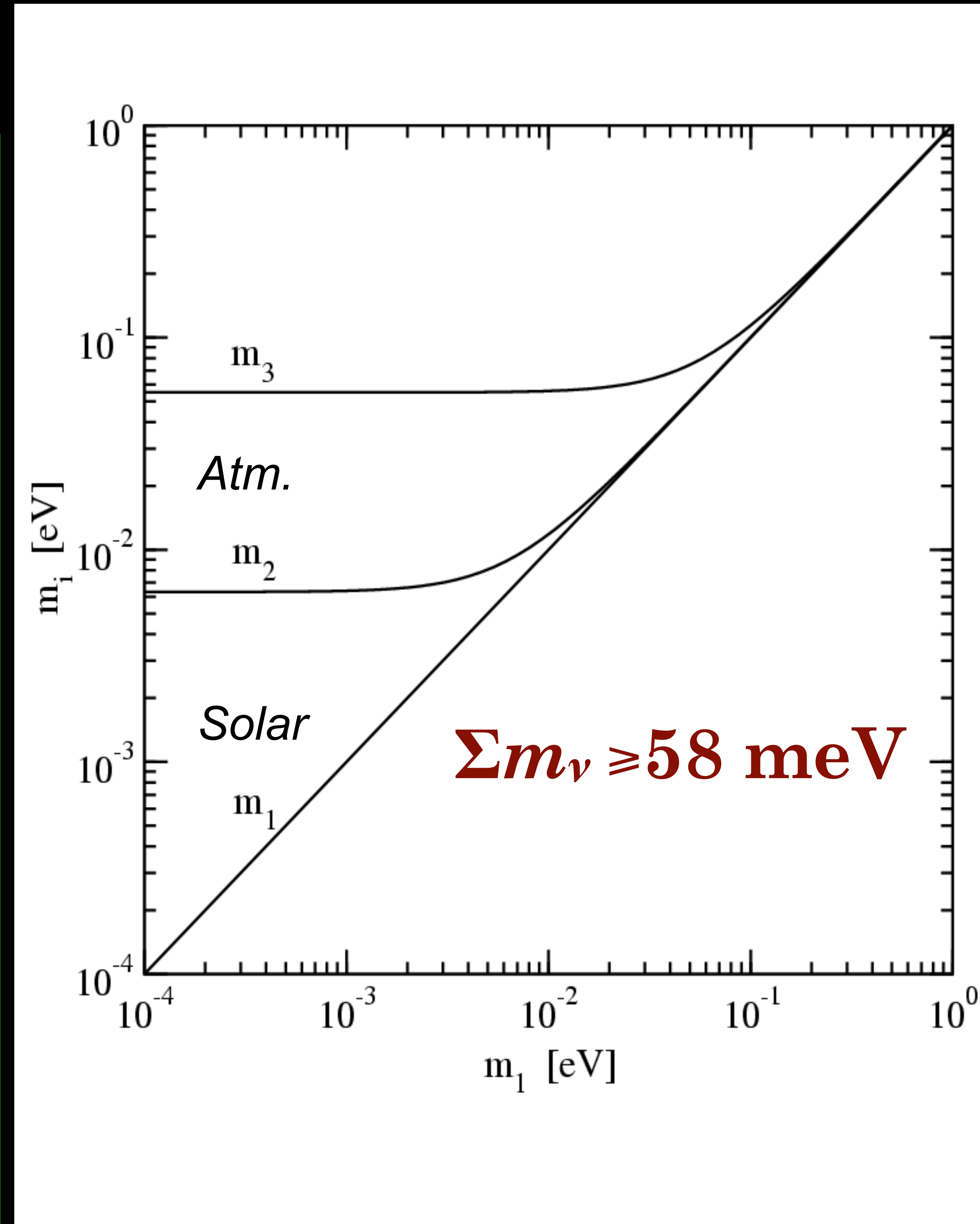




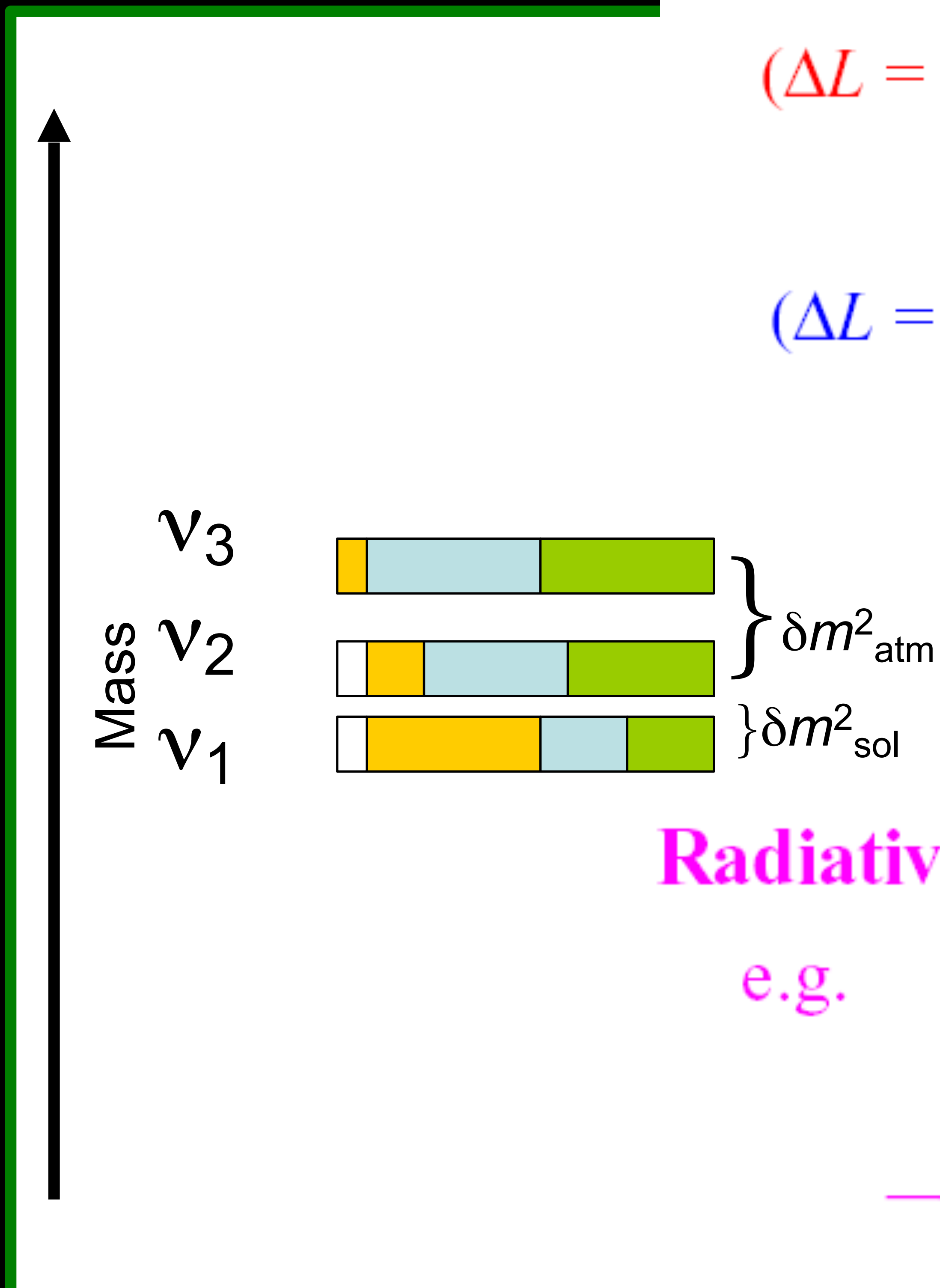


The absolute neutrino mass scale



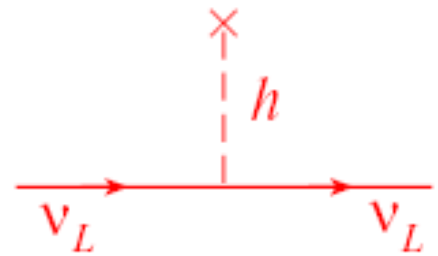


What is the absolute neutrino mass scale?



Tree-level mass generation

$(\Delta L = 0)$



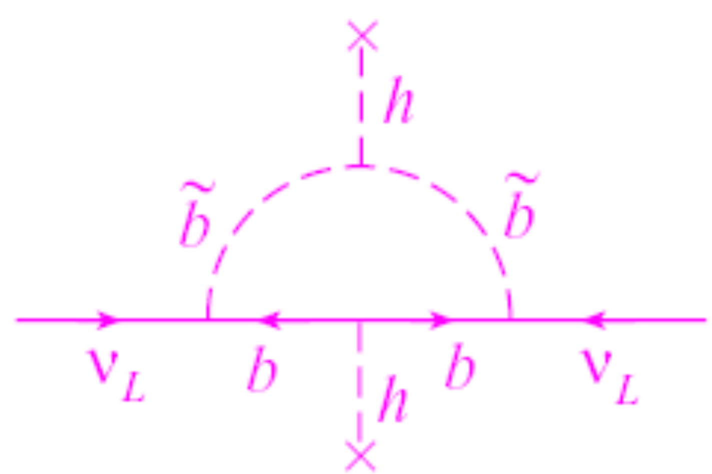
Dirac mass m_D

$(\Delta L = 2)$

Majorana mass m_M

Radiative mass generation via new interactions

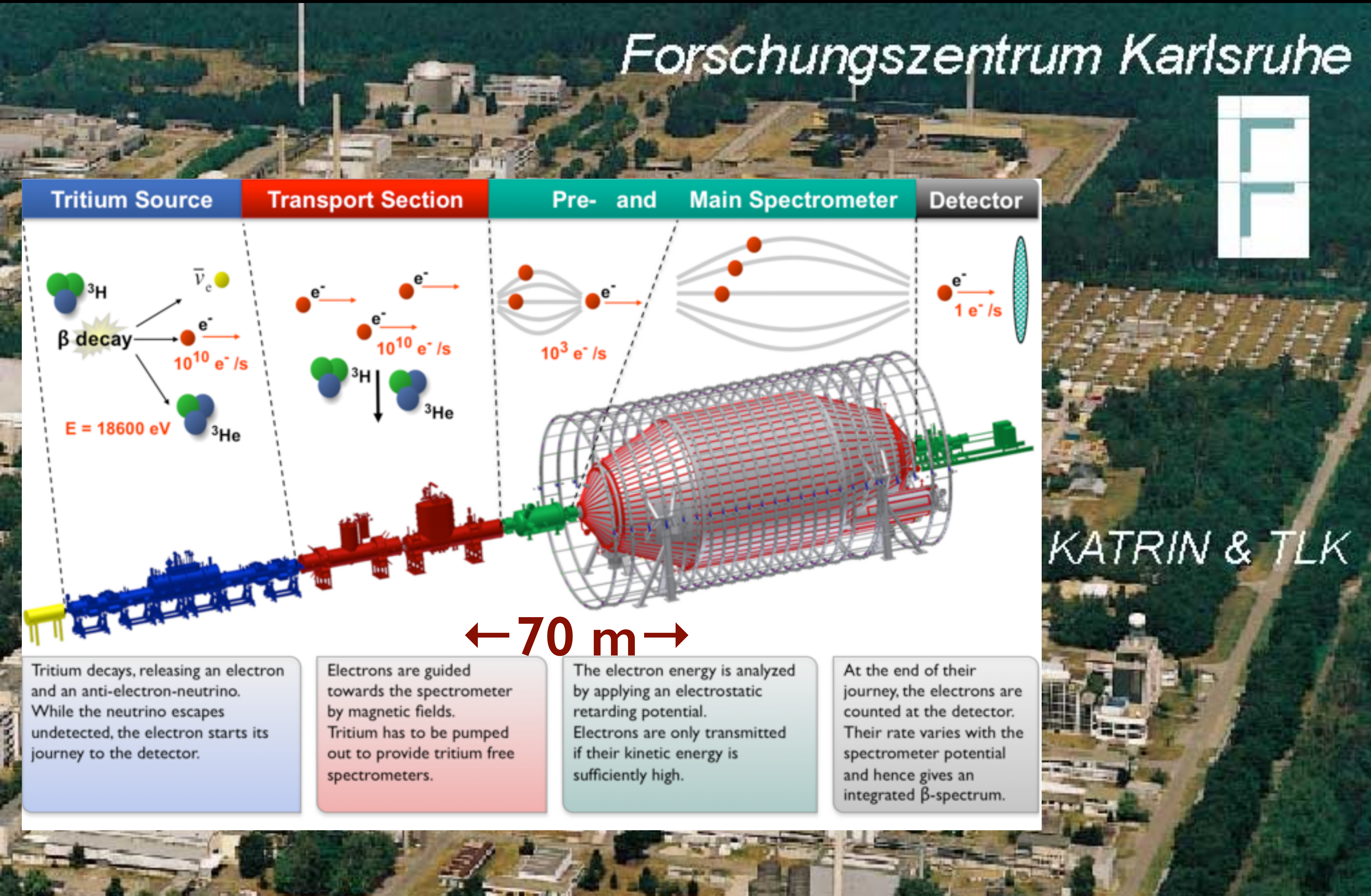
e.g.



Ma and Sarkar (98)
Drees et al. (98)

Cheung & Kong (99)
Babu (98)
Mohapatra & Senjanovic (81)
Zee (80)

The absolute neutrino mass scale in the laboratory



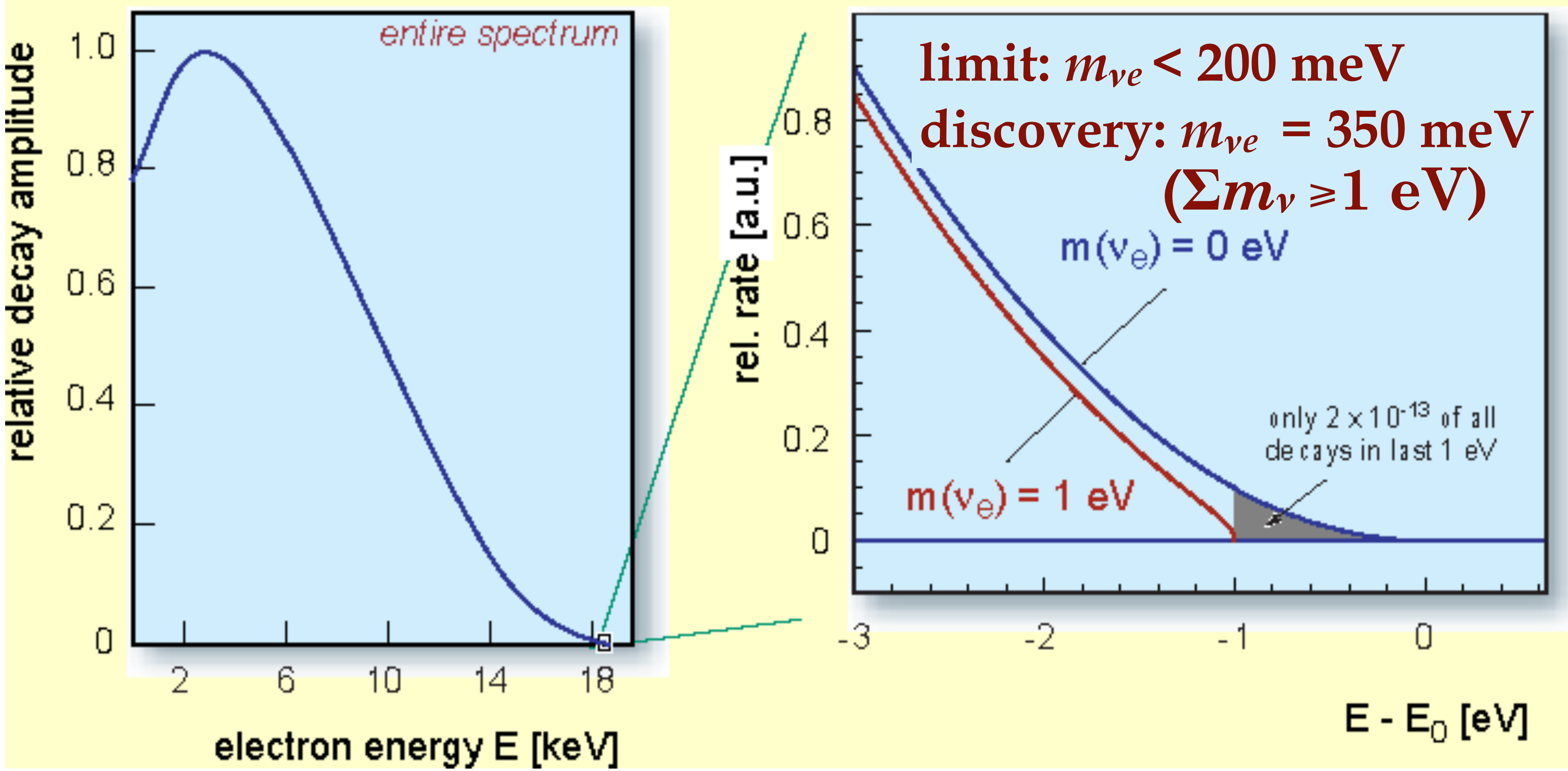
tritium ß-decay and the neutrino rest mass

$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

superallowed

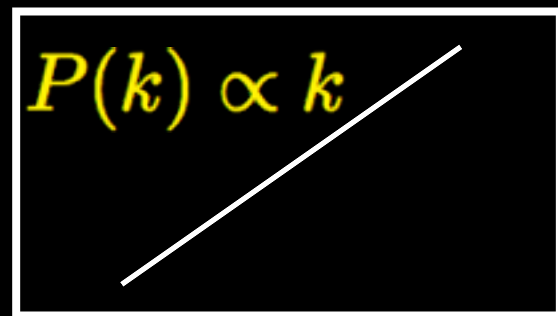
half life : $t_{1/2}$ = 12.32 a

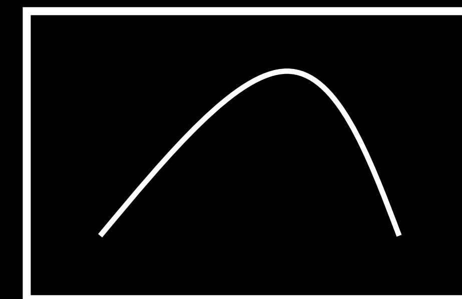
ß end point energy : E_0 = 18.57 keV



The Cosmological Matter Power Spectrum

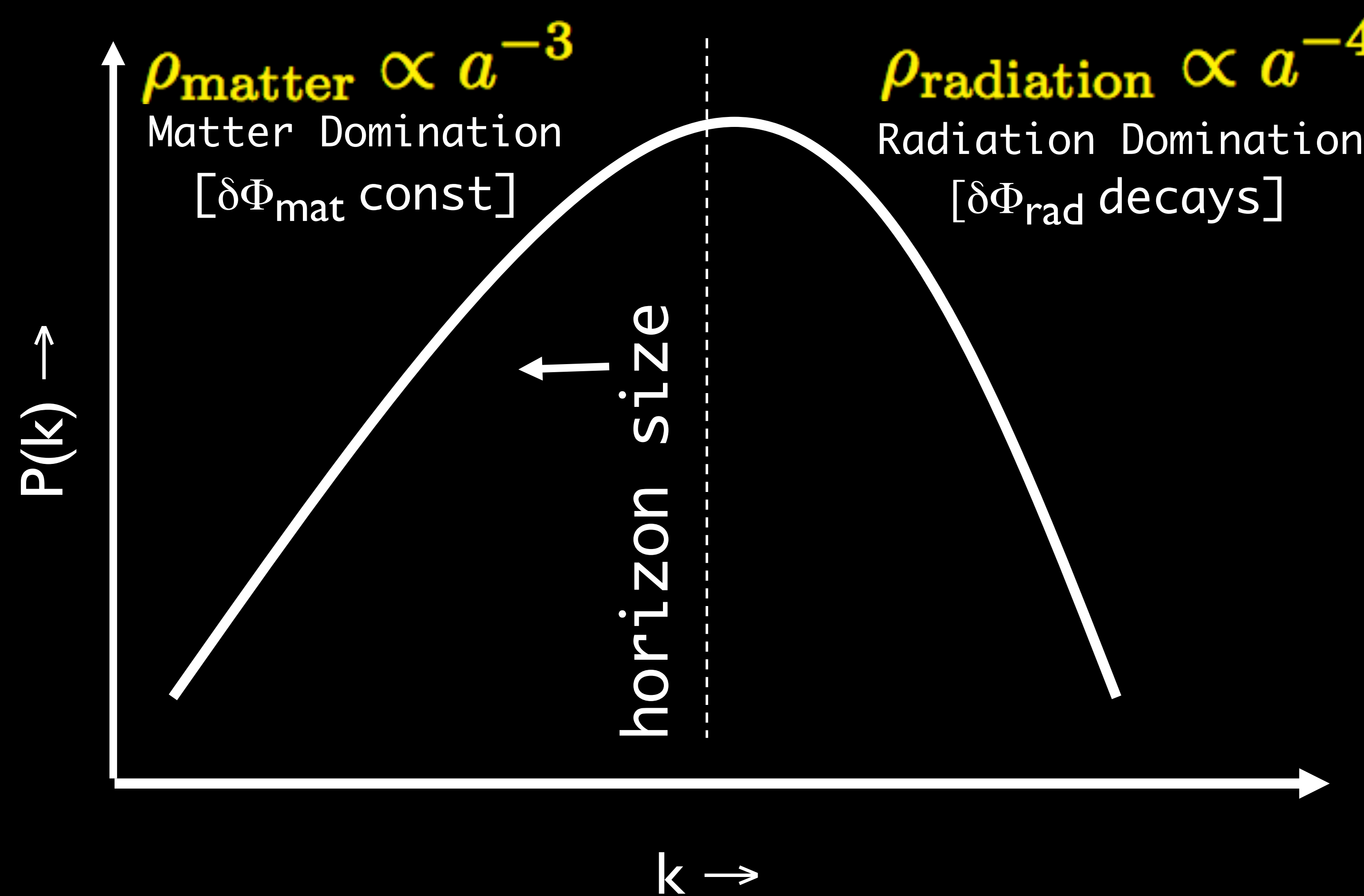
Inflation:

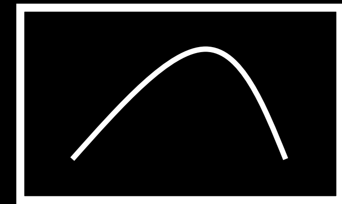




?

Perturbations enter horizon:



How does  probe neutrinos?

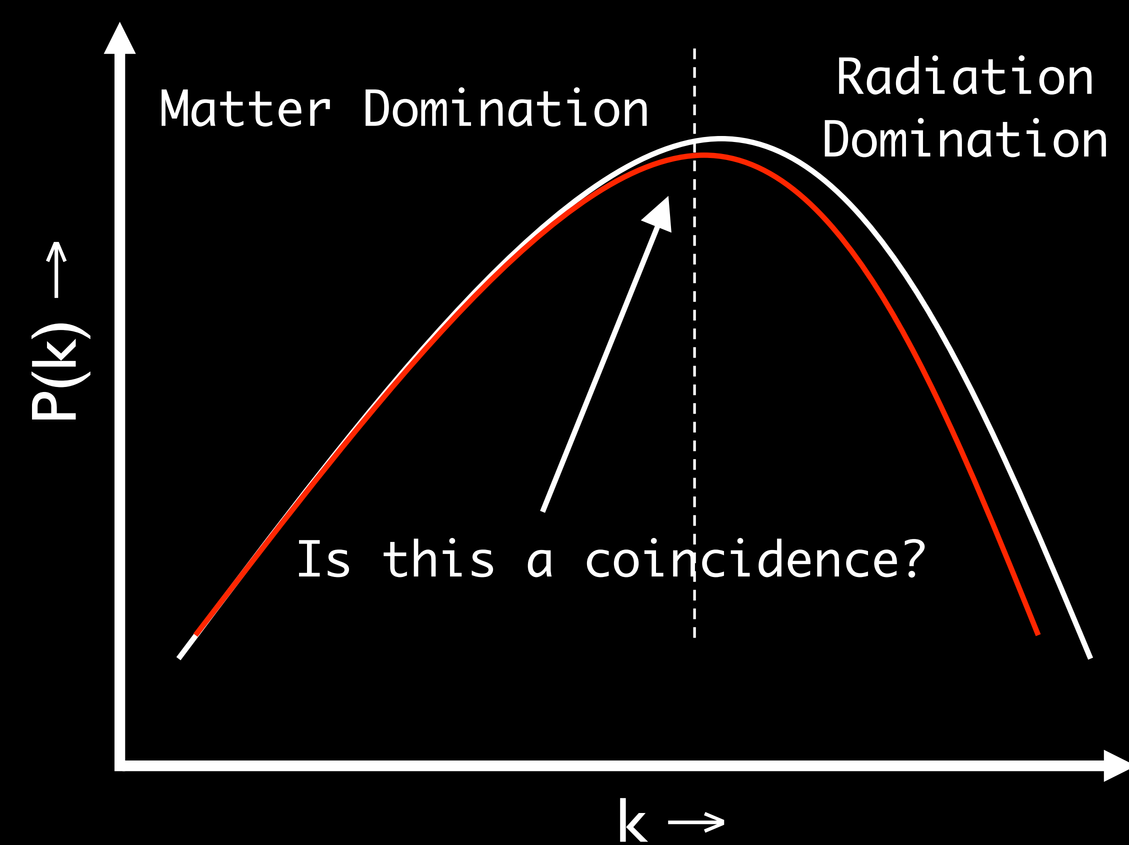
$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340\ \mathrm{cm}^{-3}$$

(Assuming thermal equilibrium)

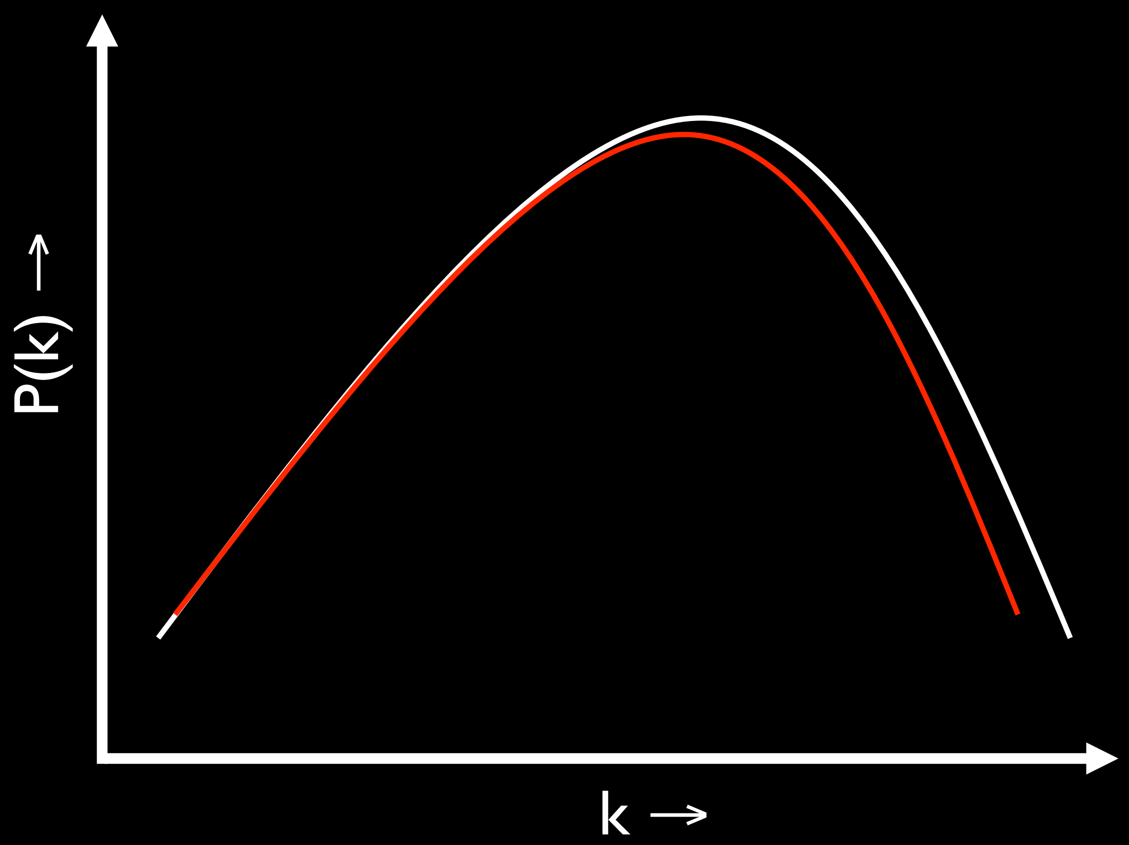
$$\rho_\nu = \sum m_i n_{\nu_i}$$

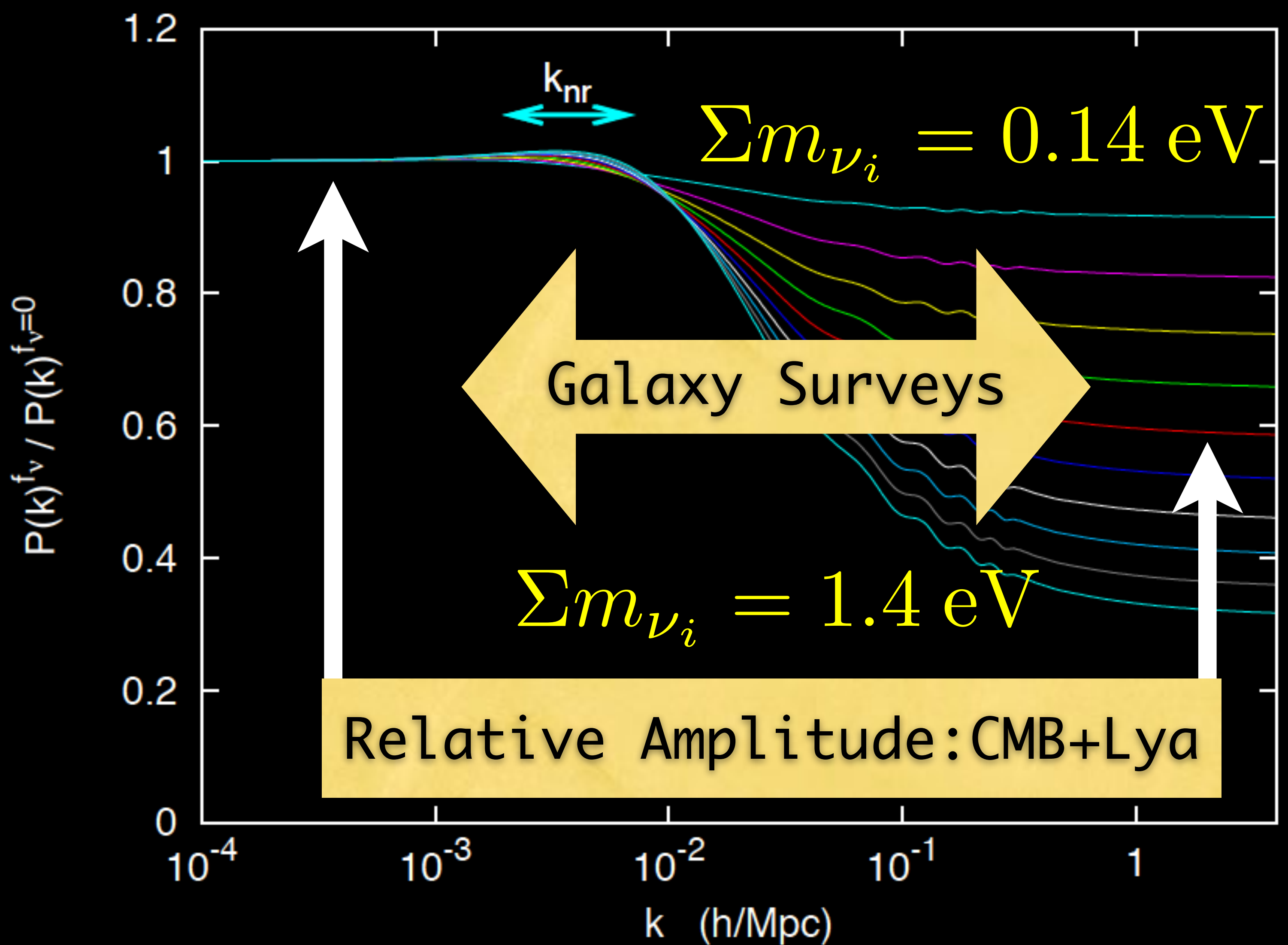
$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

$$E^2 = p^2 + m^2$$



Distinguishing Features in the Power Spectrum

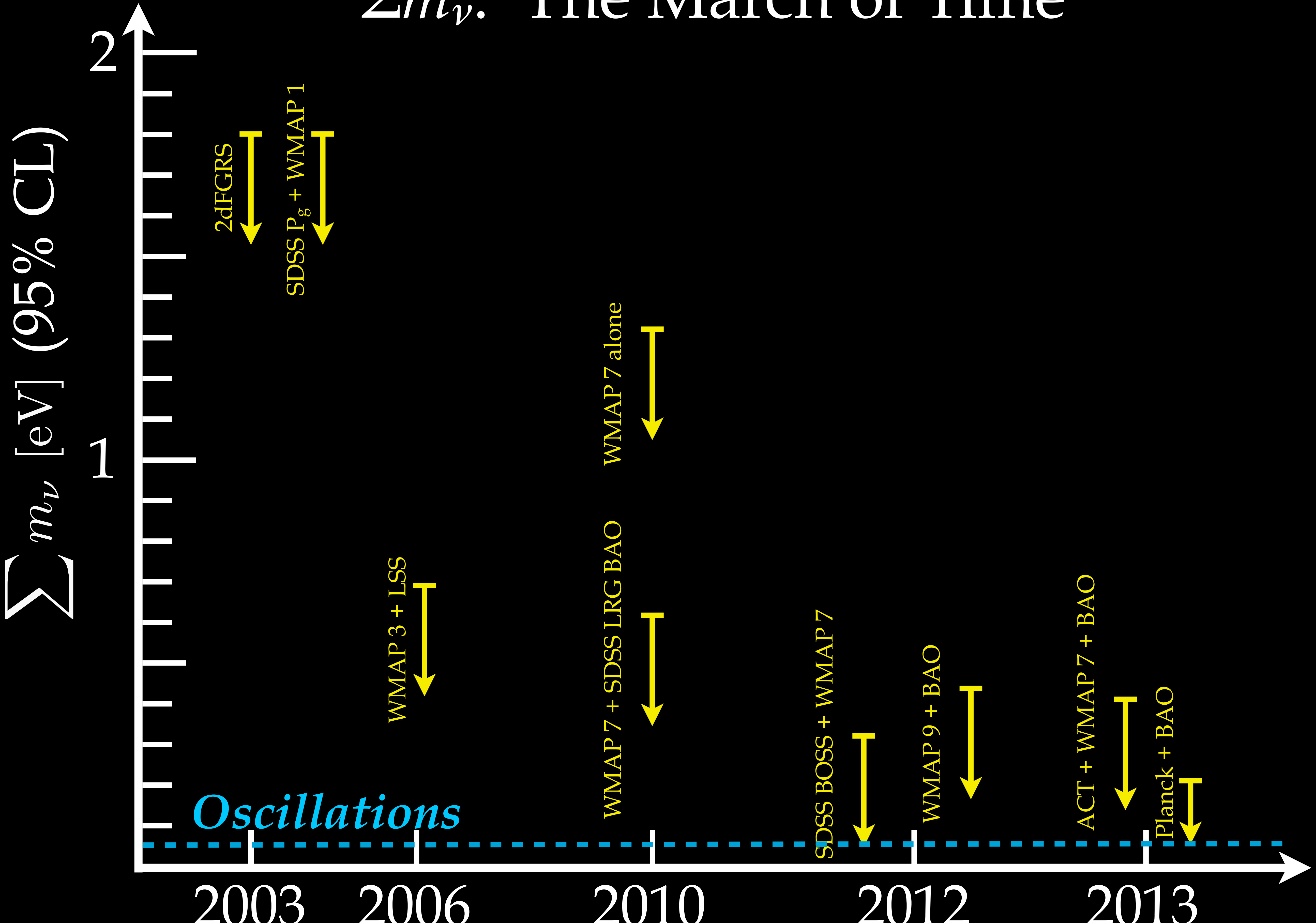


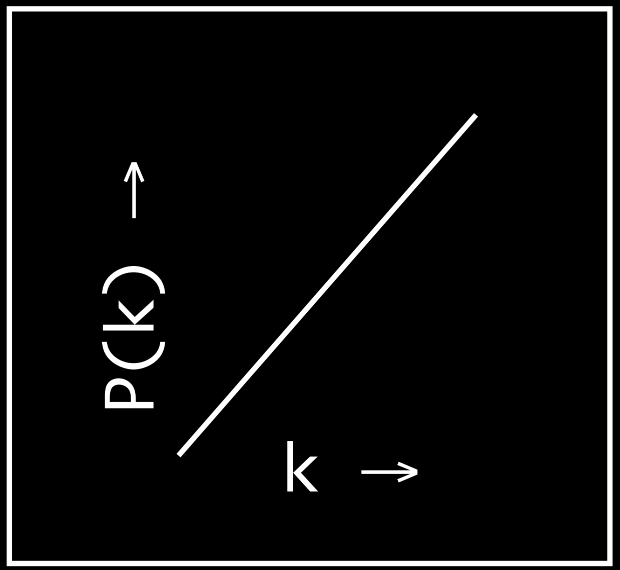


1. Shape Information:
   Galaxy Surveys (Future: CMB lensing, Weak Lensing)

2. Relative Amplitude Information:
   CMB plus Lyman-alpha Forest, Galaxy Bias $\dfrac{\Delta P(k)}{P(k)} = -8\dfrac{\Omega_\nu}{\Omega_m}$

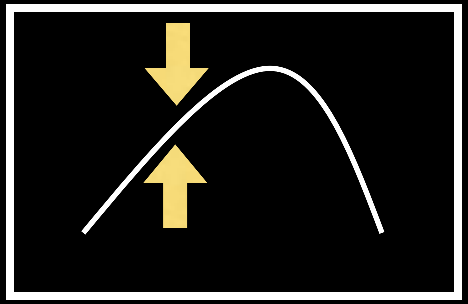
Σm_ν: The March of Time





The Primordial Spectrum: CMB gives a Precision Determination at Large Scales

$$P(k) = Ak^n$$

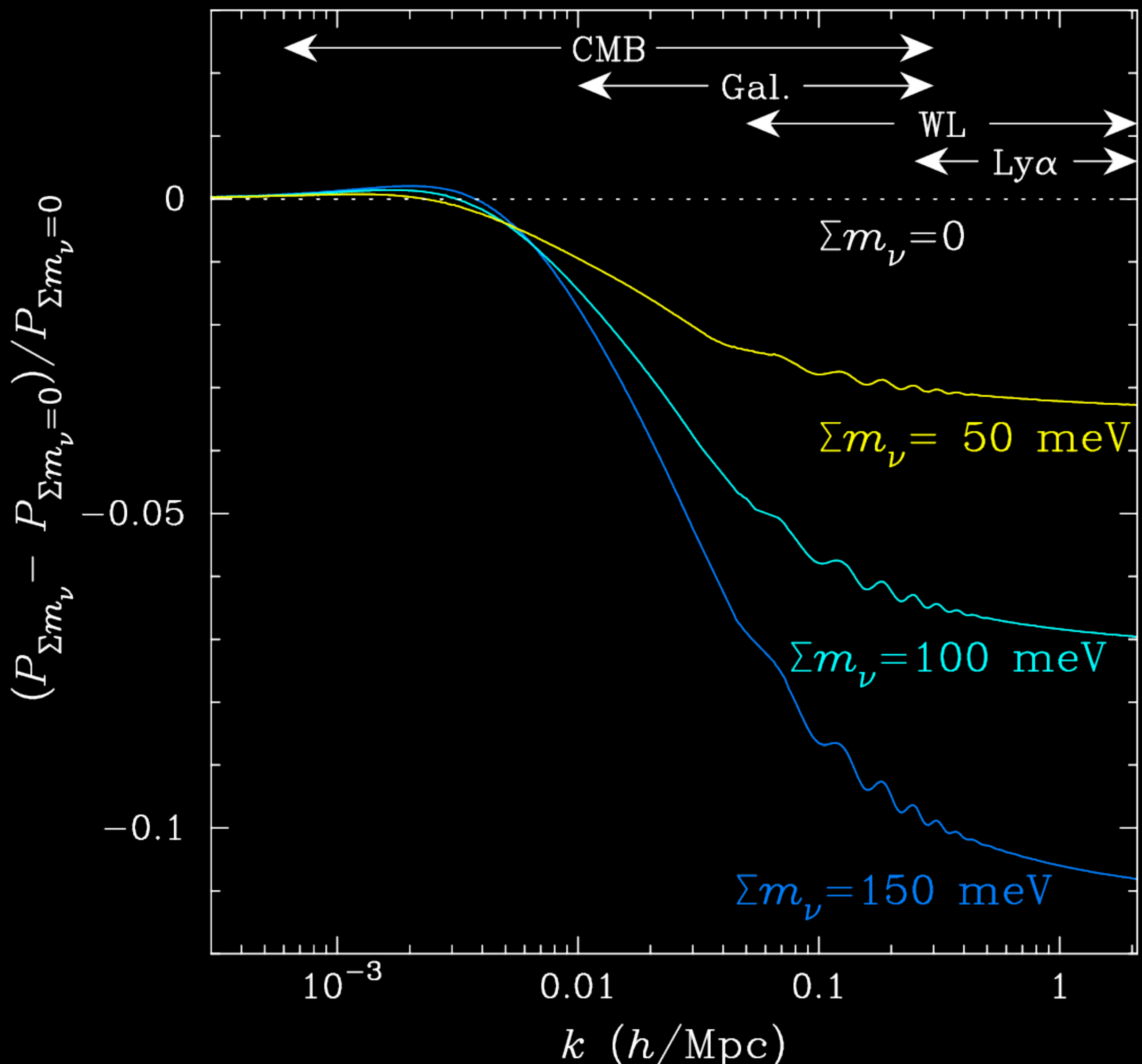


Planck 2013 + WMAP Pol.: (Planck Collab. 2013)

$$A = 2.196^{+0.051}_{-0.060} \qquad (3\%)$$

$$n = 0.9603 \pm 0.0073 \qquad (0.8\%)$$

Upcoming high-*k* High-Precision Era: Relative Change to *P*(*k*)



Estimating Upcoming Cosmological Neutrino Mass Sensitivities

$$\frac{\Delta P(k)}{P(k)} \approx 1\% \approx -8\frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein & Tegmark 1998

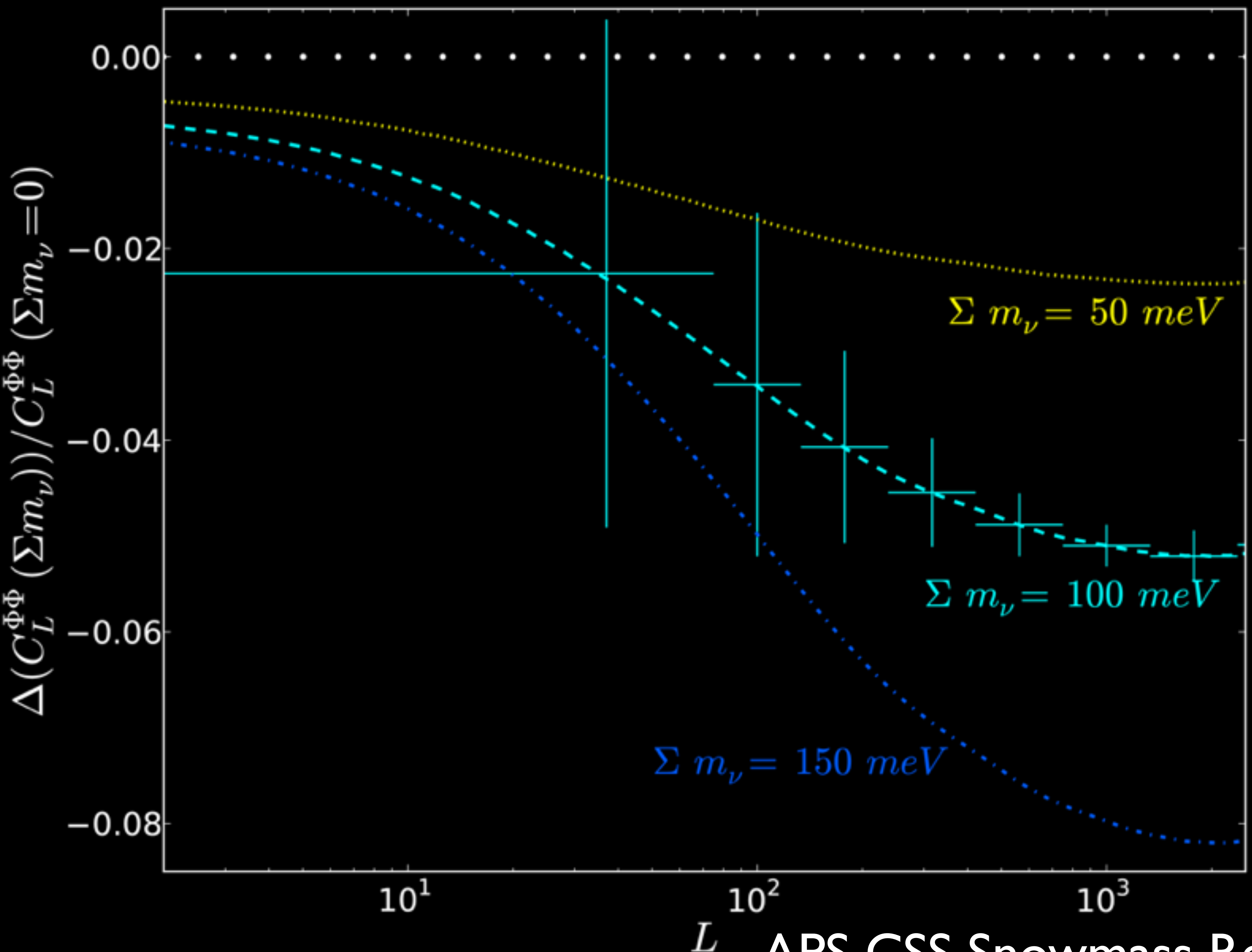
$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

$$\Longrightarrow m_\nu \lesssim (1\%/8) \times \Omega_m (93h^2\ \mathrm{eV})$$

$$\Longrightarrow m_\nu \lesssim 20\ \mathrm{meV}$$

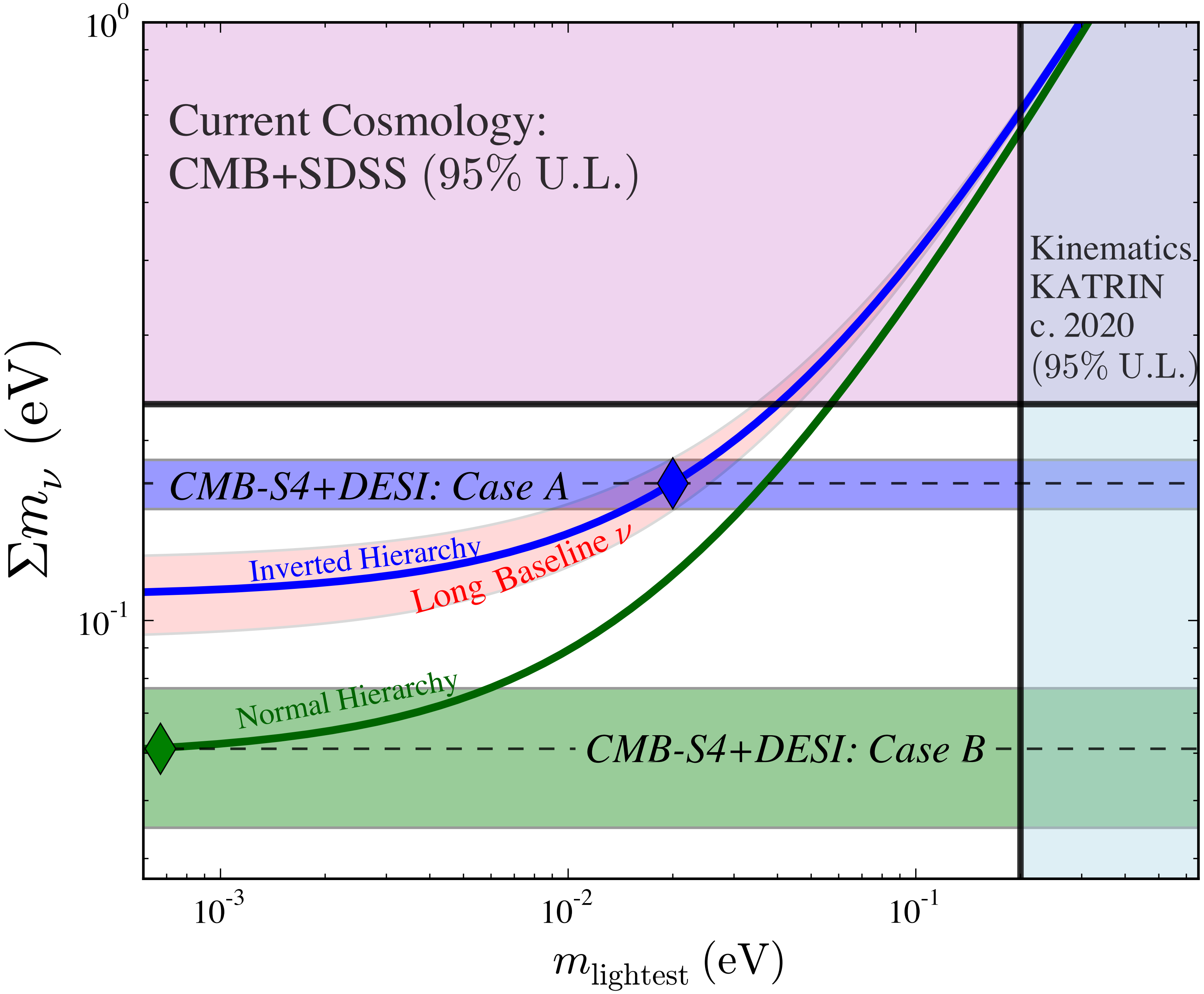
Kaplinghat et al PRL 2003 (CMB WL)
Wang et al PRL 2005 (WL Clusters)
De Bernardis et al. 2009 (Opt. WL)
Joudaki & Kaplinghat 2011 (LSST)
Basse et al. 2013 (Euclid)
Abazajian et al. 2014 (Snowmass Report)
Wu et al. 2014 (CMB-S4 + DESI)

Lensing Potential Power: Relative Change over an Integrated $P(k)$



APS CSS Snowmass Report 2013

Cosmological & Laboratory Complementarity



CMB-S4 and DESI galaxy survey BAO 1-σ sensitivities are, at optimal design:

$\sigma(\Sigma m_\nu)$ = 15 meV
$\sigma(N_{\rm eff})$ = 0.016

providing > 3σ sensitivity to the oscillation-required Σm_ν =58 meV and >2σ sensitivity to $N_{\rm eff}$

CMB alone:
$\sigma(\Sigma m_\nu)$ = 34 meV
$\sigma(N_{\rm eff})$ = 0.016

(Wu+ 2014)

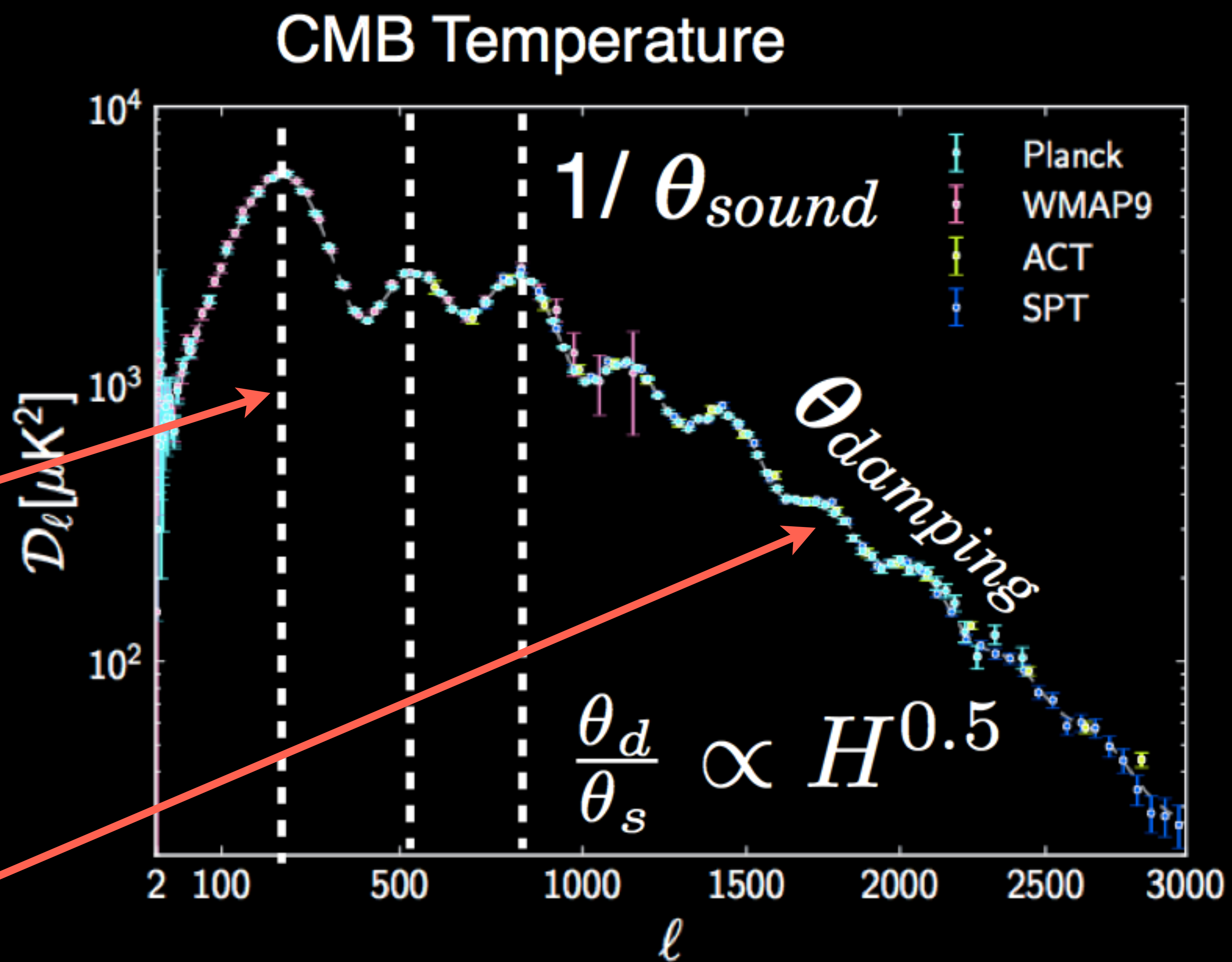
N_{eff} Effects on CMB

$$\boxed{\frac{\theta_{\text{damping}}}{\theta_{\text{sound}}} \propto H^{1/2}}$$

Larger N_{eff} Leads to More Damping

Angular scale of acoustic peaks $\theta_{\text{s}} \sim r_{\text{s}}/D$ is known precisely

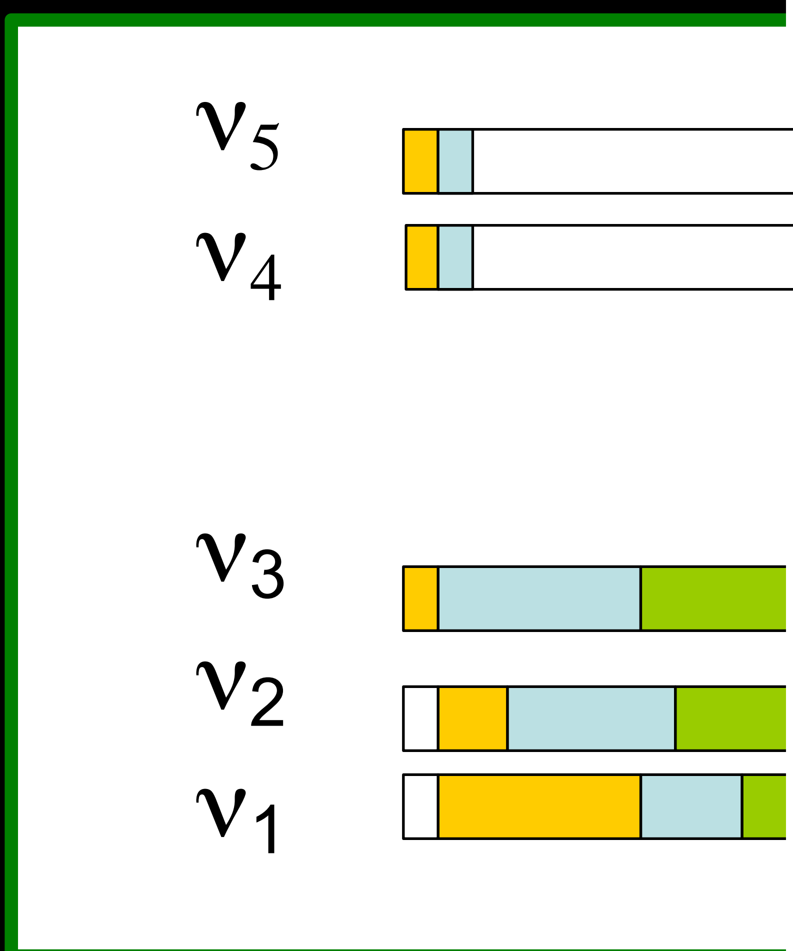
Angular scale of damping $\theta_{\text{d}} \sim r_{\text{d}}/D$ measured recently

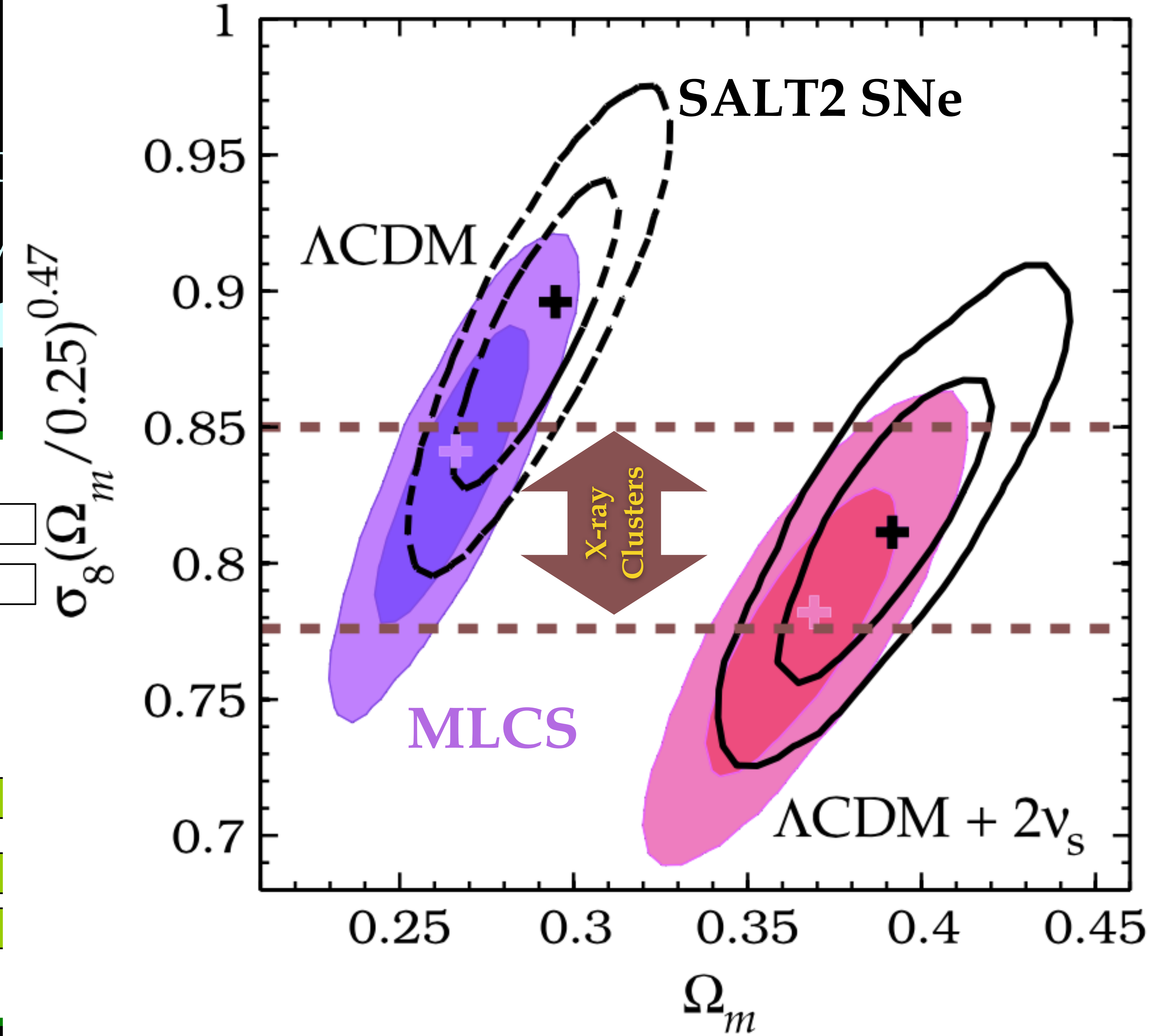


The Need for Cross-Analysis Between Neutrino Experiment and Cosmology

Joudaki, Abazajian & Kaplinghat 2013

⇒ Short baseline c
require, minimally
2 sterile ν's with s
masses, mixings





Neutrino energy density beyond the standard model e.g., via lepton number generation

1. Extra Neutrino Flavors: $\nu_s, \nu_{s'}, \nu_{s''}$ …
   Models: 2+2, 3+1, 3+2, 3+N …

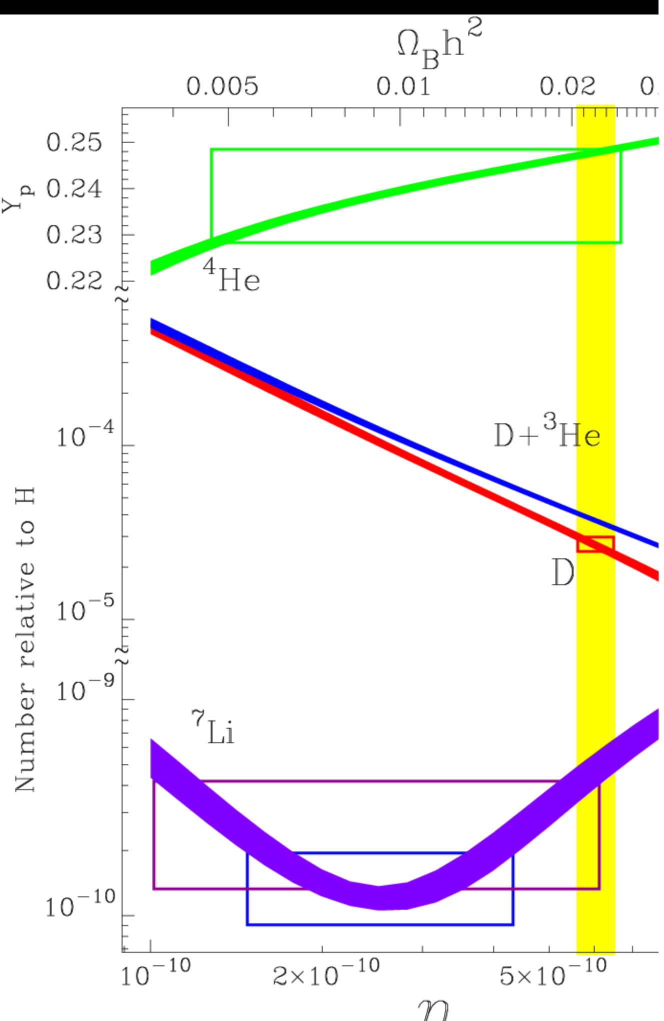
2. Neutrino Asymmetry from a leptogenesis:

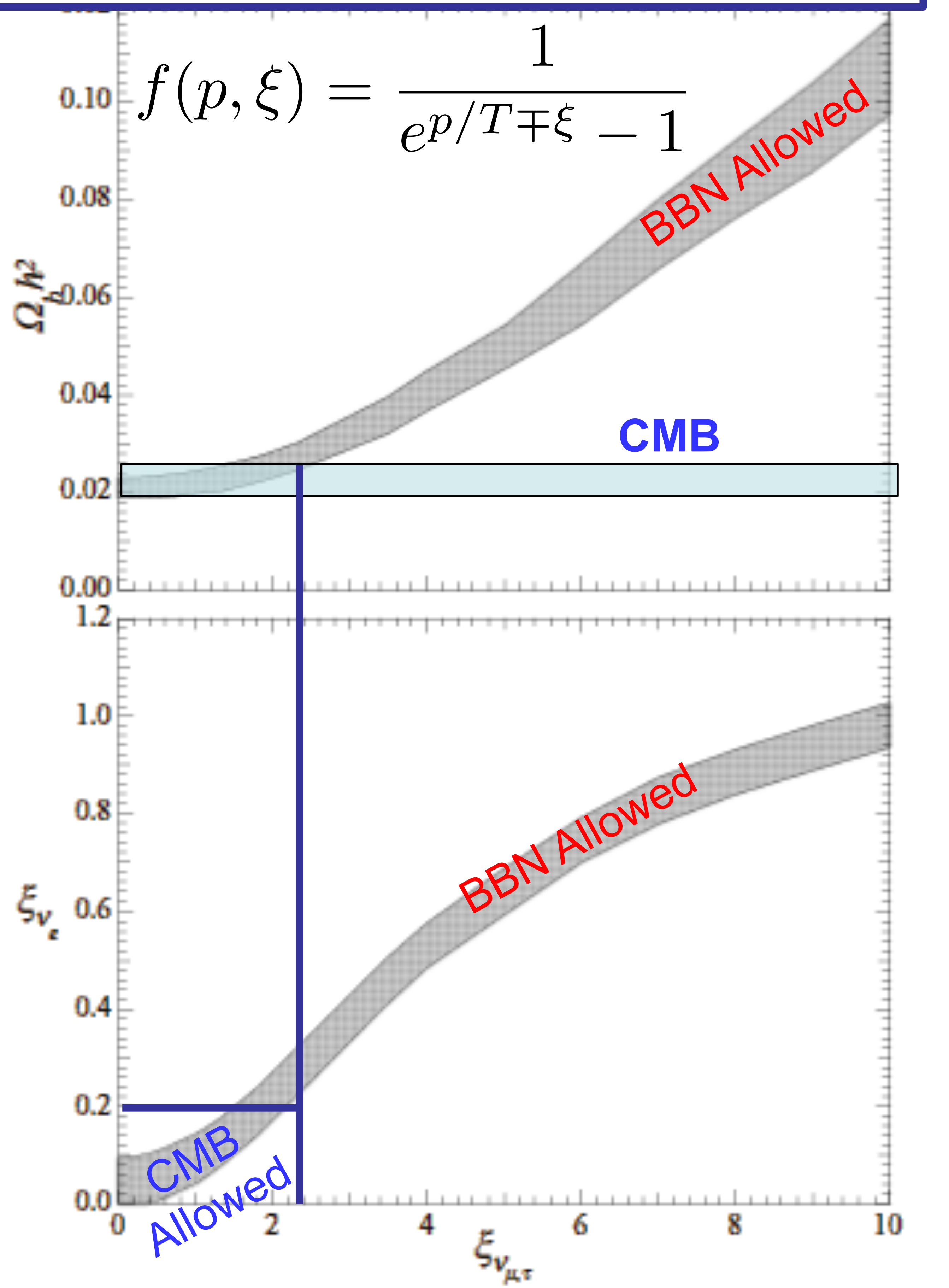
$$\rho_\nu + \rho_{\bar\nu} = \frac{1}{2\pi^2}\int_0^\infty dp\, p^2 E_\nu \left(f_\nu(p) + f_{\bar\nu}(p)\right)$$

$$f(p, \xi \equiv \mu/T) = \frac{1}{e^{p/T \mp \xi} - 1}$$

$$\Delta N_\nu = \frac{30}{7}\left(\frac{\xi}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi}{\pi}\right)^4$$

“Degenerate” Big Bang Nucleosynthesis





Using the observed abundances of D, ^{4}He, and ^{7}Li alone,

BBN is very pliable to allow large neutrino asymmetries

Due to cancelling effects between

$\nu_{\mu/\tau}$ and ν_e,

and baryon

density, $\Omega_b h^2$

Orito et al ’02

Quantum statistics with early universe neutrinos

Bloch Equations

$$\rho(p) = \frac{1}{2}[P_0(p) + \mathbf{P}(p)\cdot\sigma]$$
$$= \frac{1}{2}\begin{pmatrix} P_0(p) + P_z(p) & P_x(p) - iP_y(p) \\ P_x(p) + iP_y(p) & P_0(p) - P_z(p) \end{pmatrix}$$

Such that:

$$n_{\nu_\alpha}(p) = \frac{1}{2}[P_0(p) + P_z(p)] \qquad n_{\nu_\beta}(p) = \frac{1}{2}[P_0(p) - P_z(p)]$$

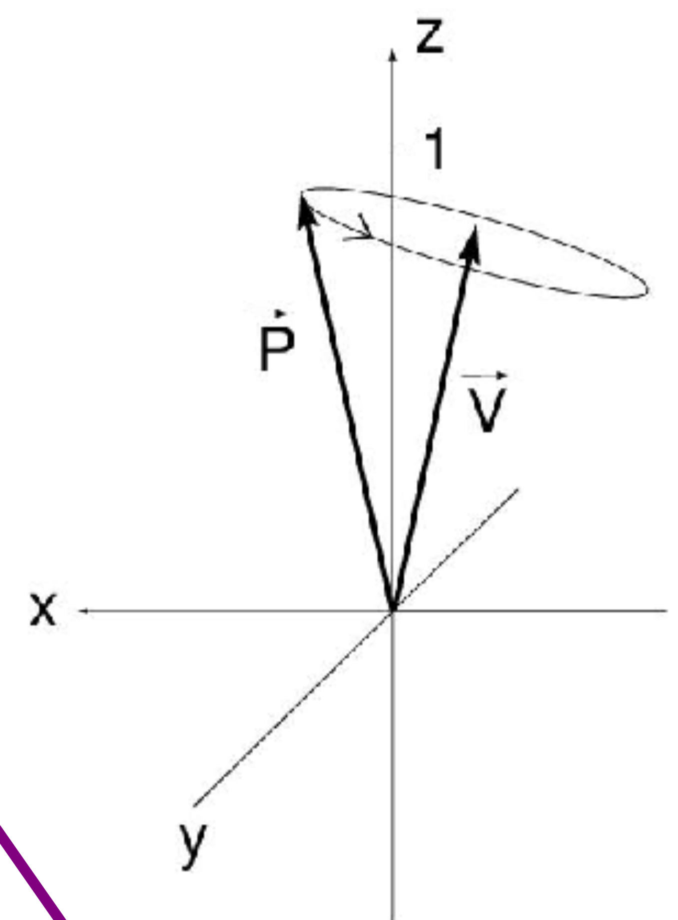
Evolution of the density matrix for a homogeneous two-flavor neutrino gas plus background ($e^\pm$, $\mu^\pm$...) is generally

$$\dot{\mathbf{P}}(p) = \mathbf{V}(p)\times\mathbf{P}(p) + \left[R_\alpha(p) - R_\beta(k)\right]\hat{\mathbf{z}} + \mathcal{C}[\mathbf{P}(p)]$$

$$\dot{P}_0(p) = R_\alpha(p) + R_\beta(p)$$

Coherent Behavior

$$\partial_t \mathbf{P}(p) = \mathbf{V}(p) \times \mathbf{P}(p)$$



$$\mathbf{V}(p) = \mathbf{\Delta}(p) + \left[V^B(p) + V^T(p)\right]\hat{\mathbf{z}} + \mathbf{V}^S(p)$$

...dipole precession in a magnetic field

Vacuum Oscillation

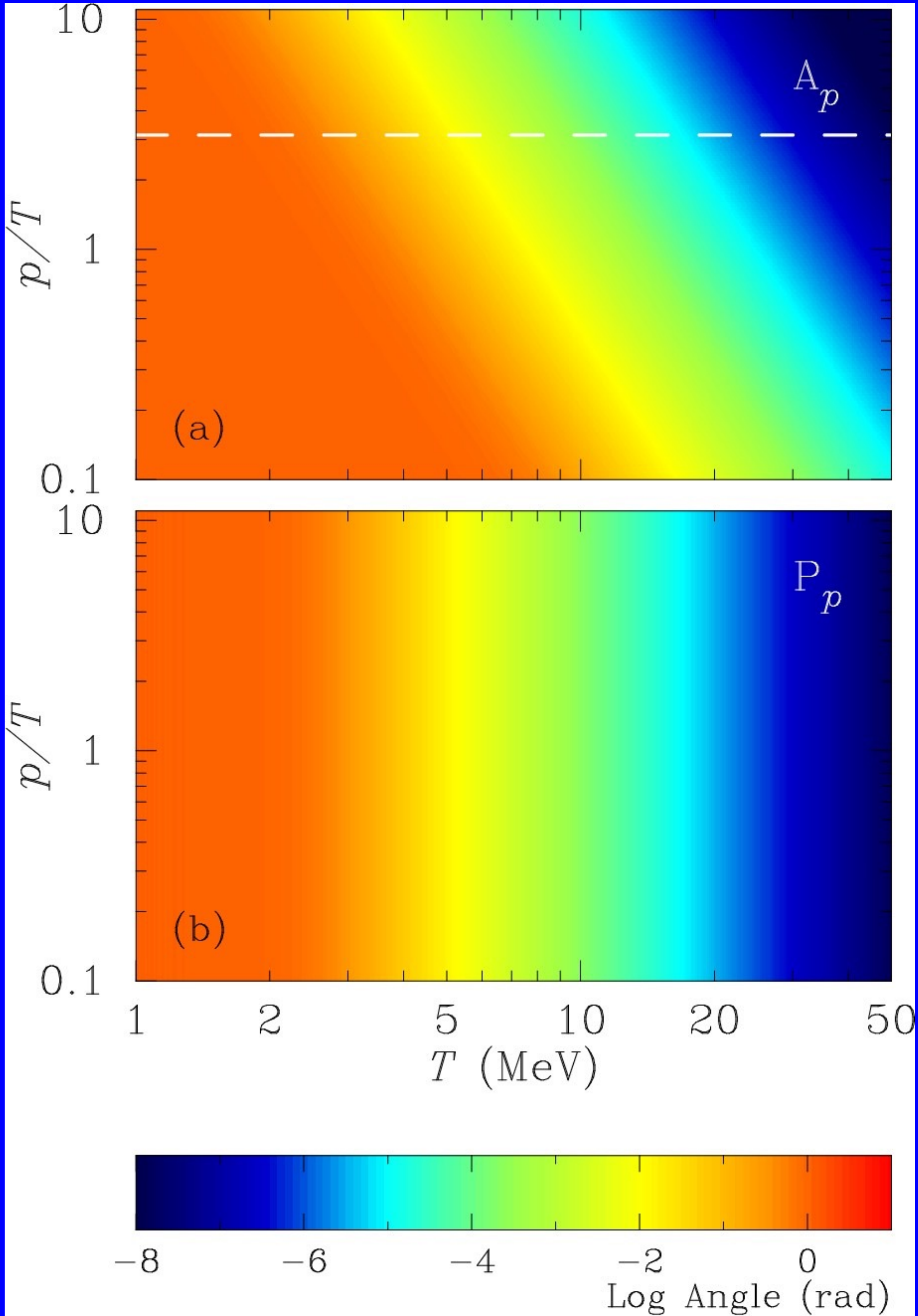
$e^{+/-}$ / $\mu^{+/-}$ background

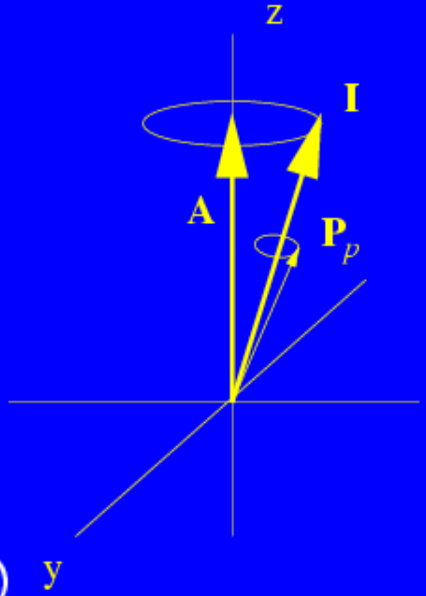
Thermal Potential

(finite temperature effects)

Neutrino Self-Potential

Neutrino Flavor Momentum Synchronization…





Collectively:

$$\partial_t \mathbf{I} = \mathbf{A}_{\text{eff}} \times \mathbf{I}$$

Assuming $\mathbf{I} \,||\, (\mathbf{P}_p + \bar{\mathbf{P}}_p)$:

$$\mathbf{A}_{\text{eff}} \simeq \frac{1}{\mathbf{I}^2} \int \mathbf{A}_p (\mathbf{P}_p + \overline{\mathbf{P}}_p)$$

follows...

$$\mathbf{A}_{\text{eff}} \equiv \Delta_{\text{sync}} \left(\sin 2\theta_{\text{sync}} \hat{\mathbf{x}} - \cos 2\theta_{\text{sync}} \hat{\mathbf{z}} \right),$$

$$\boxed{\frac{p_{\text{sync}}}{T} = \pi \sqrt{1 + \xi^2 / 2\pi^2} \simeq \pi}$$

while the average for a FD distribution is

$$\boxed{\langle p/T \rangle = \frac{7\pi^4}{180\zeta(3)} \simeq 3.15}$$

$$\mathbf{\Delta}(p) = \frac{\delta m^2}{2p} (\sin 2\theta_0, 0, -\cos 2\theta_0)$$

Large to maximal mixing is essential...

Abazajian, Beacom & Bell
2002

The Death of Degenerate BBN and New Constraints…

Constraints on ν_e asymmetry:

$$\Delta\xi_e \approx \frac{\Delta Y_p}{Y_p}$$

Conservatively, errors

$$\frac{\Delta Y_p}{Y_p} \approx 0.1 \Rightarrow \Delta\xi_e$$

or, more accurate accounting gi

$$0.03 \lesssim \xi_e \lesssim 0.0$$

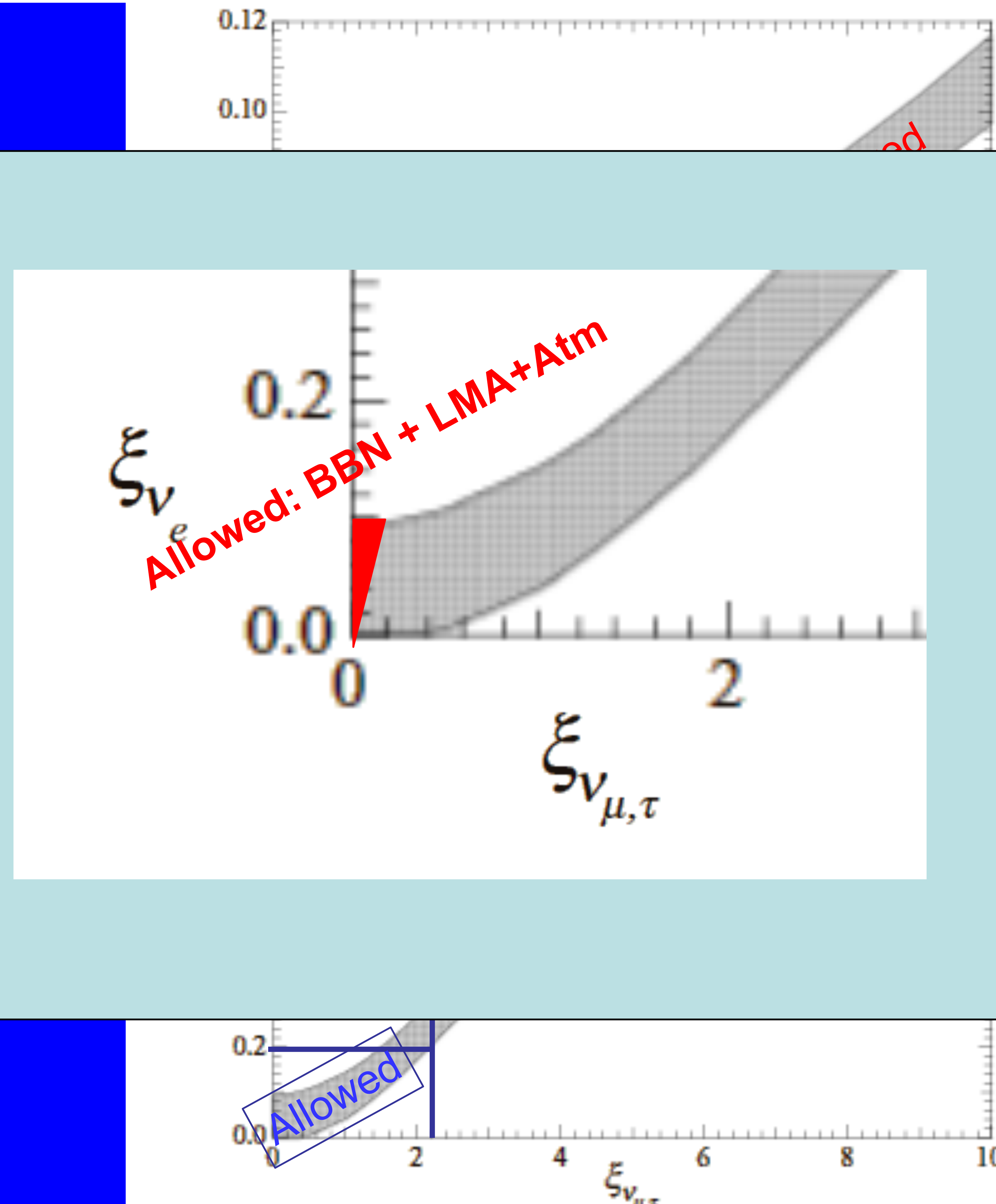
$$|L_e| \lesssim 0.1$$

and

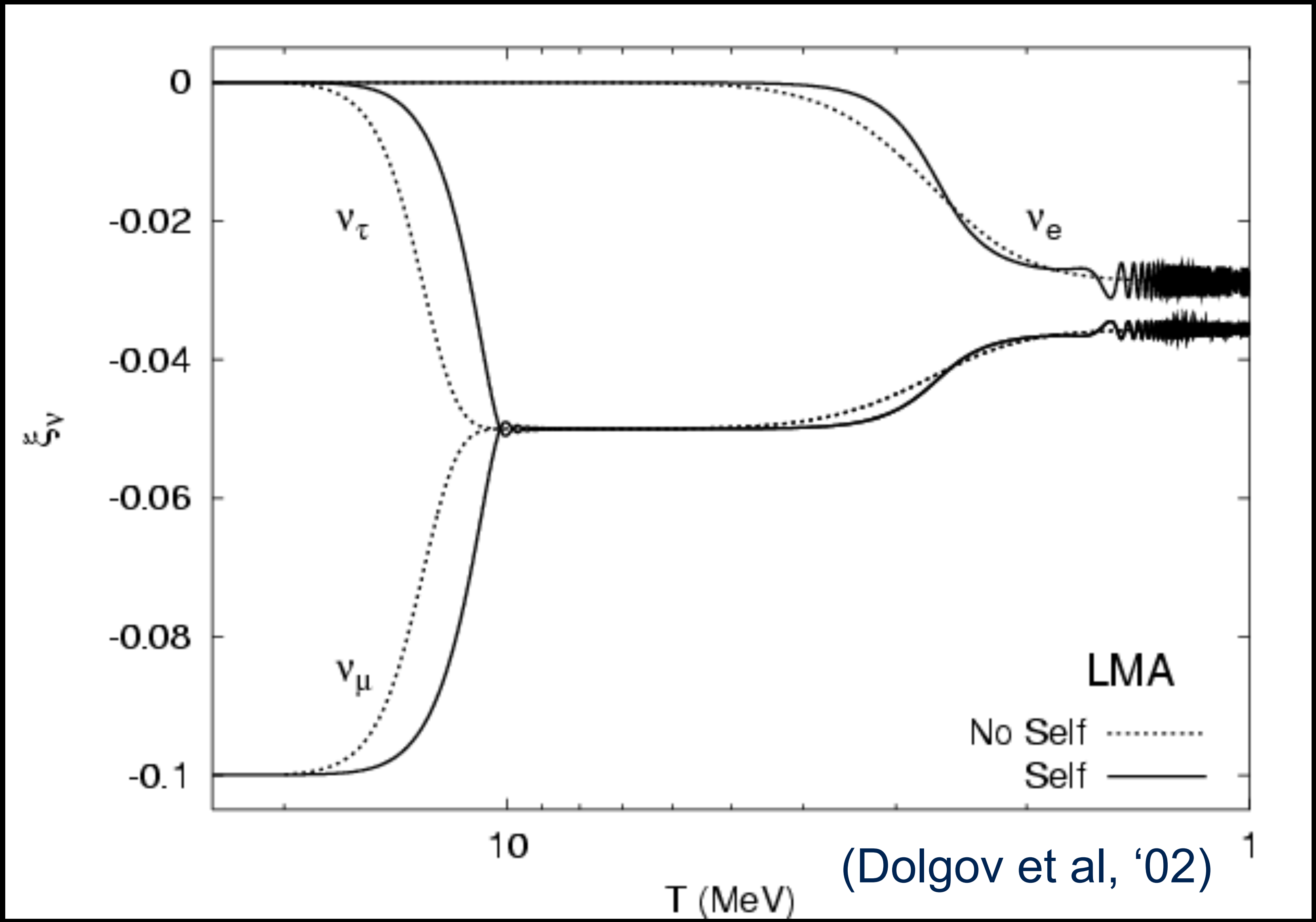
$$\xi_e^f = \left(\frac{1-\cos 2\theta_0}{2}\right.$$

$$\xi_{\mu^*}^f = \left(\frac{1+\cos 2\theta_0}{2}\right.$$

$$\Rightarrow |L_\mu + L_\tau| \lesssim 0.5$$



Transformation of neutrino asymmetries



(Dolgov et al, '02)

LMA solar + maximal ATM

→Any chemical potential will alter the ^{4}He abundance.

$$\xi \ll 1 \Longrightarrow \Delta N_\nu < 0.04$$

The claimed standard abundance of N_{eff} (standard) = 3.046 is uncertain to within this order of magnitude due to oscillation effects during decoupling

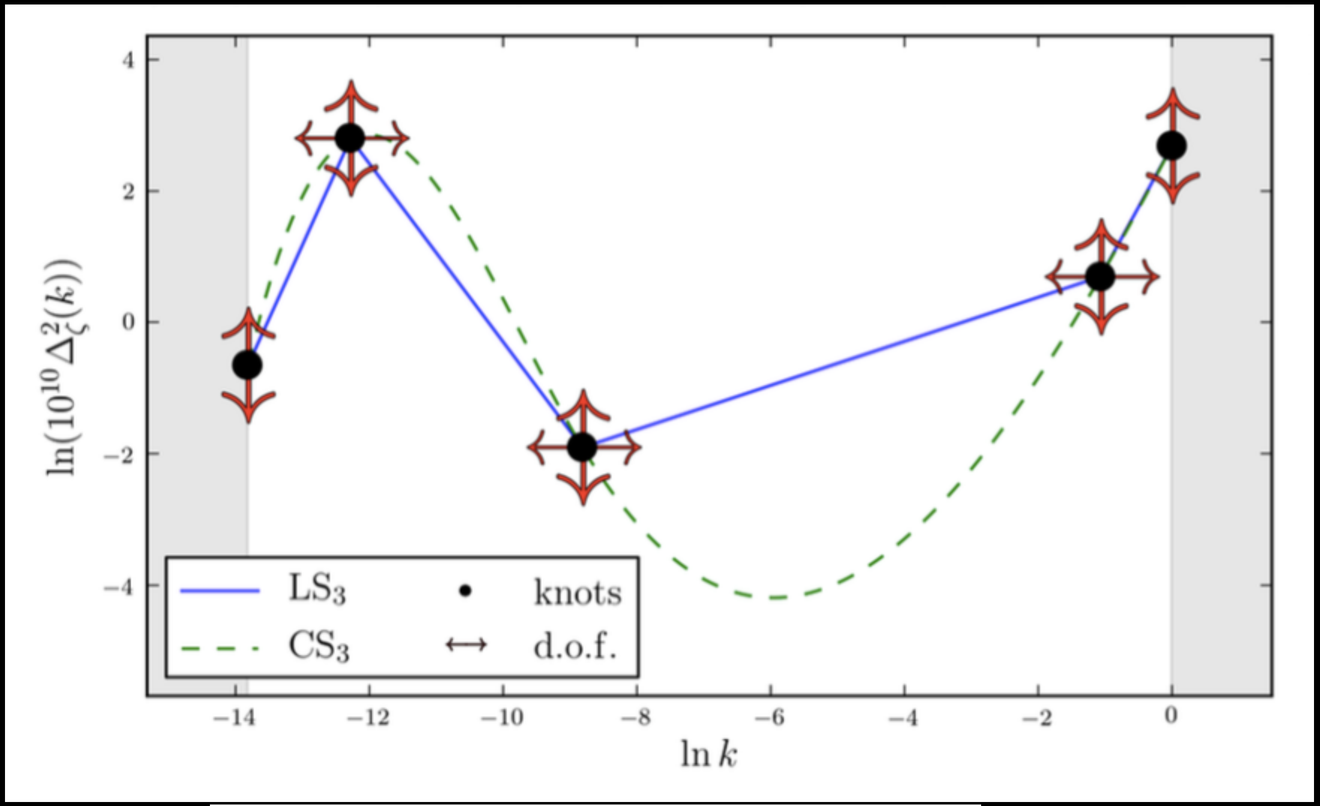
More general density:

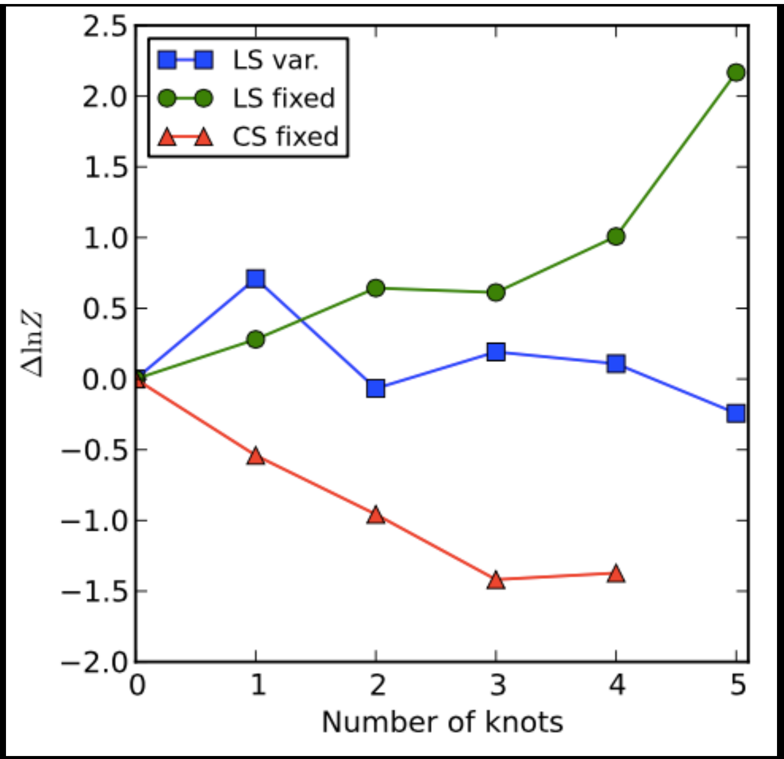
$$n_\nu = \left(\frac{3}{11}\right)\frac{2\zeta(3)}{\pi^2}T^3F_2(\xi)$$

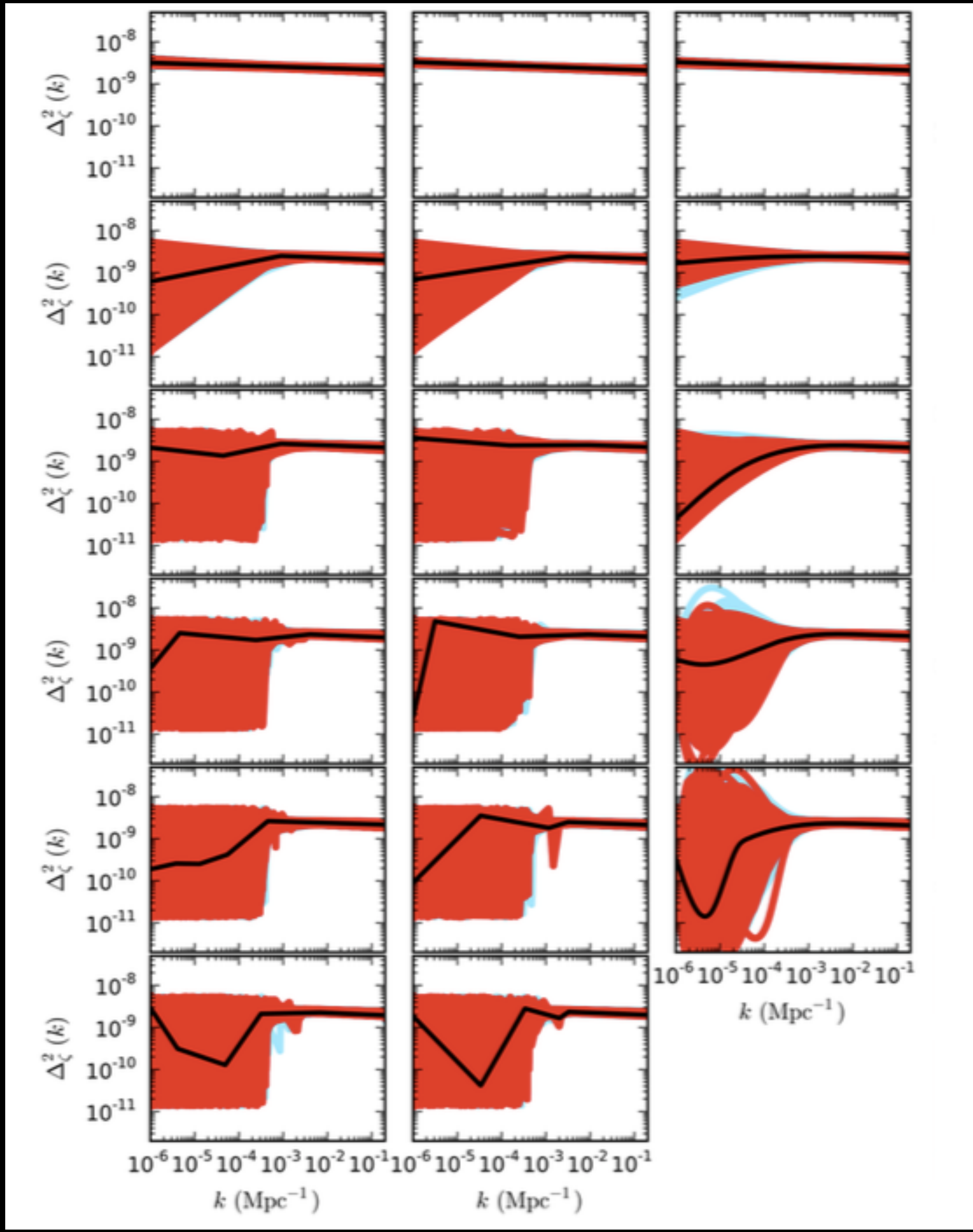
$$\approx 113\ \text{cm}^{-3}\ F_2(\xi)$$

Signals of deviations from a power law primordial power spectrum in the CMB?

Aslanyan, Price, Abazajian & Easther 2014

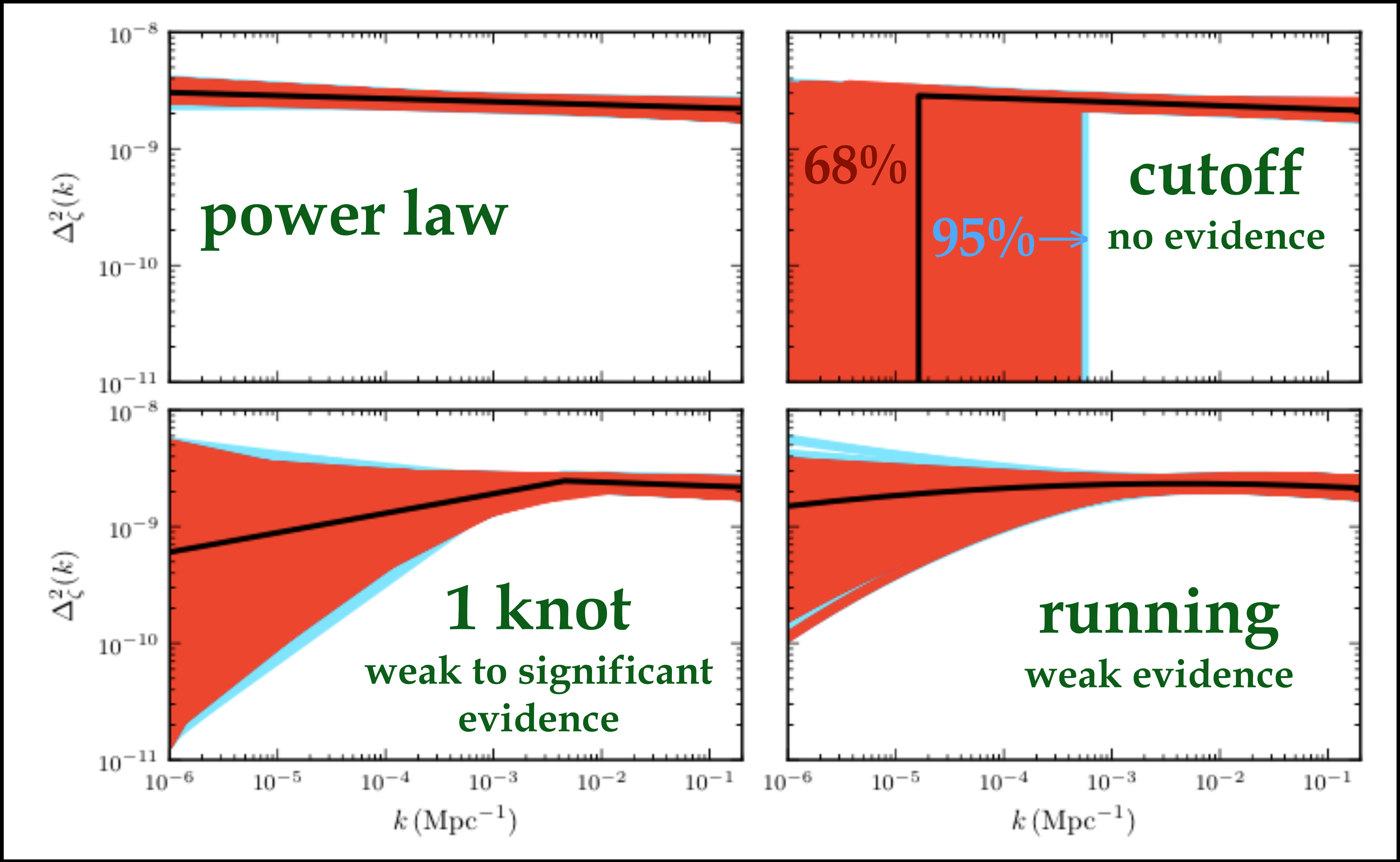






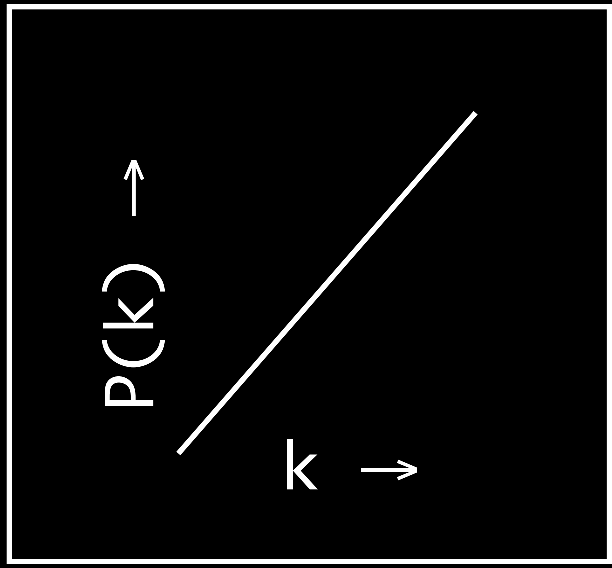
Signals of deviations from a power law PPS in the CMB **with BICEP2 relic *B*-modes**?

Abazajian, Aslanyan, Easther & Price 2014

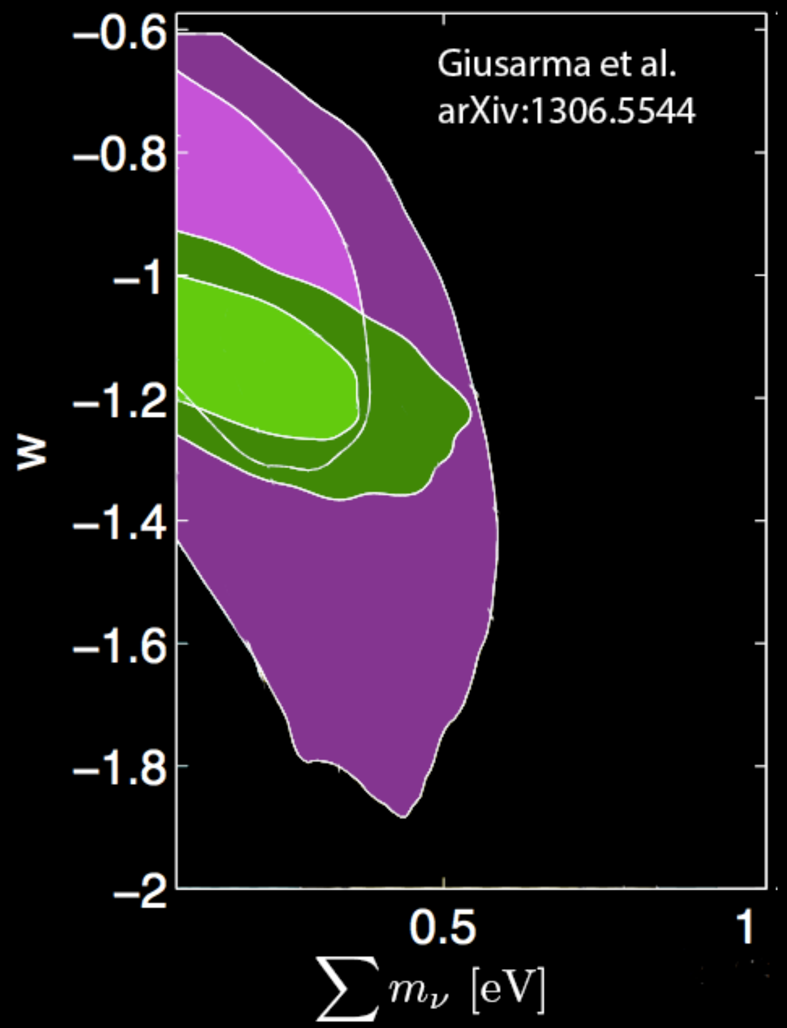


Neutrino Mass from Cosmology: What would break if cosmology and neutrino experiment disagree?

1. Primordial power spectrum $P(k)$ is a simple power law



2. No other prevalent "non-vanilla" cosmological parameters and physics: w, N_{eff}, modified gravity...



Summary

- Cosmology has the strongest inferred experimental sensitivity on the total neutrino mass, and are forecast to maintain that position.
- CMB-S4 and DESI galaxy survey 1-σ sensitivities are:

  $\sigma(\Sigma m_\nu)$ = 15 meV &
  $\sigma(N_{\rm eff})$ = 0.016

  providing > 3σ sensitivity to the oscillation-required Σm_ν =58 meV and >2σ sensitivity to $N_{\rm eff}$ (Wu+ 2014)
- The neutrino background is not necessarily the simplest possible case. Asymmetries from lepton number generation, extra neutrino density from massive particle decay, and new neutrino interactions could all reveal themselves.
- ***Other relativistic energy density can be present.***
- **What if we do not detect the minimal model?**
  *If the minimal neutrino sector, with Σm_ν = 58 meV and N_{eff} = 3.046, is **not** robustly detected, it would imply something is "off" in another aspect or aspects of cosmology, including possibly:* non-constant dark energy, a non-power-law primordial perturbation spectrum, extra particle or radiation species, non-zero curvature, as well as other possibilities, e.g., a nonthermal cosmological neutrino background.